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RADIOACTIVE DUST SAMPLING. PART 4: LONG-LIVED RADIOACTIVE DUST (LLRD) CHARACTERIZATION AND LLRD INSTRUMENT EVALUATION IN TWO URANIUM MILLS

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RADIOACTIVE DUST SAMPLING
PART 4: LONG-LIVED RADIOACTIVE DUST (LLRD) CHARACTERIZATION AND LLRD INSTRUMENT EVALUATION IN TWO URANIUM MILLS

J. Bigu* and A. Frattini**

ABSTRACT

This technical report is part of a series of reports on the characterization of Long-Lived Radioactive Dust (LLRD) and the technical evaluation of several dust monitoring instruments in common use in specialized laboratory and field work, e.g., uranium mines and mills. The data reported here pertain to an experimental study conducted in two uranium mills in the province of Saskatchewan (Cluff Lake and Key Lake). The study was carried out with a twofold purpose in mind, namely, for the characterization of dust and LLRD, and for the evaluation of a variety of monitoring instruments including cascade impactors, optical particle counters, nylon cyclones, open face filter samplers, and α-particle personal dosimeters, the latter normally used for α-particle radiation exposure purposes. Agreement between the data using the above devices was, in general, fair to good.

Key words: Radiation instrumentation; Radioactive dust; Dust.

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ÉCHANTILLONNAGE DES POUSSIÈRES RADIOACTIVES
PARTIE 4 :CARACTÉRISATION DES POUSSIÈRES RADIOACTIVES DE LONGUE PÉRIODE (PRLP) ET ÉVALUATION D'INSTRUMENTS DE MESURE DES PRLP DANS DEUX MINES D'URANIUM

J. Bigu* et A. Frattini**

RÉSUMÉ

Le présent rapport technique fait partie d'une série de rapports portant sur la caractérisation des poussières radioactives de longue période (PRLP) et l'évaluation technique de plusieurs instruments de surveillance des poussières d'utilisation courante dans des travaux spécialisés effectués en laboratoire ou sur le terrain, par exemple dans des mines et des usines de concentration d'uranium. Les données présentées ont trait à une étude expérimentale effectuée dans deux usines de concentration d'uranium de la Saskatchewan (Cluff Lake et Key Lake). On a réalisé l'étude en visant un double objectif : caractérisation des poussières et des PRLP et évaluation d'une variété d'instruments de surveillance, notamment des impacteurs en cascade, des compteurs de particules optiques, des cyclones en nylon, des échantillonneurs à filtres à face ouverte et des dosimètres alpha personnels, ces derniers étant normalement utilisés pour l'exposition au rayonnement alpha. La compatibilité entre les données obtenues avec les dispositifs susmentionnés était généralement de passable à bonne.

Mots clés : Instruments de mesure des rayonnements; poussière radioactive; poussière.

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INTRODUCTION

Milling operations generate dust emissions within a wide particle size range. Of particular interest from the occupational hygiene and health physics standpoints are dusts generated in the respirable particle size range from about 1 μm to approximately 10 μm. Dusts in this particle size range, once inhaled, will be deposited in different parts of the respiratory system where they can pose a potential health hazard.

Dust generated in uranium mills contains the parents of the natural uranium and thorium radioactive decay chains as well as their long-lived and short-lived decay products. In addition to the 'natural' airborne long-lived radioactive dust (LLRD) found in uranium mill atmospheres, generated mainly as a result of milling operations and other activities, selectively concentrated amounts of certain long-lived radionuclides, such as U (in yellowcake), are also found in uranium mill atmospheres as a result of the U-concentrating process.

Because of the potential occupational health hazards associated with the inhalation of LLRD, its characterization is of great interest. However, accurate characterization of LLRD requires reliable instrumentation. The purpose of the present study was twofold:

1. To characterize LLRD in two uranium (U) mills;
2. To evaluate in the uranium mills the performance of a number of dust monitoring instruments in common use in field and laboratory applications.

This work was requested by the Atomic Energy Control Board (AECB) as part of a contract awarded to CANMET (E.M.R), entitled 'Comparison of Radioactive Aerosol Sampling Instruments', AECB Contract No. 4.108.1; Mining Research Laboratories (CANMET) Project No. 143902-14-4. The report presented here is part of phase 2 of the above contract which will be presented in five parts. The data in this report correspond to Part 4 of phase 2.

EXPERIMENTAL SITES

Work was conducted from February 11th to February 22nd, 1991, at two uranium mills in the province of Saskatchewan, namely Cluff Lake (Amok Ltd.), and Key Lake (Cameco). Several U-milling operations were monitored during the Long-Lived Radioactive Dust (LLRD) characterization and instrument evaluation. The following mechanical and chemical operations were preferentially studied: crushing, ore transportation, grinding, milling, yellowcake precipitation, lime slaking, and yellowcake packaging. The mill circuits, i.e., mechanical and chemical operations are shown in flow-diagram form in Figure 1 (Cluff Lake), and Figure 2 (Key Lake).

EXPERIMENTAL APPARATUS

Various monitoring instruments were used and evaluated for LLRD characterization:

1. Cascade impactors (CI) of the manual and automated type;
2. Nylon cyclones (NC);
3. Open-face filter samplers (OFFS);
4. Personal α-particle dosimeters (PADs); and
5. Optical particle counters (OPCs) with and without particle size selection capabilities.

Cascade impactors Sierra model 210 and Marple 290 (both distributed by Andersen, U.S.A.), PADS designed by the Commissariat a l'Energie Atomique (CEA, France), and total particle count OPC MiniRam model PDM-3 distributed by CGA (U.S.A.) were used. The OFFS used were of in-house design and were made up of commercially available open-face filter holders and sampling pumps. The nylon cyclones were purchased from Levitt Safety Canada Ltd. (Toronto). In addition, an automated cascade impactor (CI) using piezoelectric substrate stages (model QCM PC-2 from California Instruments, U.S.A.), and an OPC with particle size selection capabilities (model CI-7300 from CLIMET Instruments Co., U.S.A.) were also used. The samplers and monitors referred to above have been described and discussed in detail in Part 1 of phase 2 of this project (1) and will, therefore, not be discussed further.

EXPERIMENTAL MEASUREMENTS AND PROCEDURES

Evaluation of instrumentation was conducted at a number of mill working stations where measurements were divided into the following main groups:

1. Dust characterization such as concentration and size distribution;
2. Long-Lived Radioactive Dust (LLRD) concentration, and radioactivity and electrical charge (associated with the dust) size distribution;
3. Meteorological variables such as temperature (T), relative humidity (RH), and barometric pressure (P).

Sampling and measurement of the variables indicated in items 1 and 2 were made on a daily basis. Measurements indicated in item 3 were conducted several times throughout the working shift (12 h).

It has been indicated elsewhere (2) that the low sampling airflow rate of the PADs (~3.4 L/h) made it necessary for these devices to sample air for several days for a reliable reading of dust to be attained. Comparison of data obtained with the PADs and other instrumentation which sampled dust during the daily working shift was carried out by adding the results obtained (on a daily basis) for the same days as the PADs were operated. The latter were only operated at Cluff Lake. The PADs were not used at Key Lake because of the unavailability of battery chargers at this mill. The PADs were used to quantify dust and LLRD.

The OPC MiniRam PDM-3, being a dust monitor of the continuous type, provided dust concentration data on a 'real-time' basis, e.g., six independent readings per minute. Data with the open-face filter samplers (OFFS) were obtained daily. The MiniRam provided continuous monitoring of respirable dust mass, whereas the OFFS were used to measure total dust concentration and total LLRD concentration, [LLRD]. The nylon cyclones, NC, were used to determine respirable dust concentration and respirable [LLRD].

Airborne dust, and its associated long-lived α-particle activity, i.e., LLRD, versus dust particle size measurements were carried out using the cascade impactors Sierra 210 and Marple 290, instruments which also provided [LLRD] data.

The automated cascade impactor (CI) model QCM PC-2, or QCM for short, was used to determine dust mass concentration versus dust particle size, and also total dust mass concentration within the particle size range characteristics of the instrument. The CLIMET OPC, model CI-7300, or CLIMET for short, was used to determine dust particle size distribution.

Characterization of dust and of the radioactivity associated with it are presented in this report in a number of ways, namely:

1. Percentage (%) cumulative dust mass (or α-particle activity) less than the Equivalent Aerodynamic Diameter (EAD,$D_{p,50}$) versus particle size. This type of graph permits the Mass Median Aerodynamic Diameter (MMAD) and the Activity Median Aerodynamic Diameter), as well as their respective geometric standard deviations (σ_g or GSD) to be obtained. This graph can be obtained from cascade impactor data;
2. Percentage (of the total) dust mass (or α-particle activity) versus cut-off particle size for the different stages of the cascade impactors. This type of data are presented here as line graphs and as histograms (bar graphs);
3. Dust mass concentration versus time. This kind of graph is obtained from the MiniRam. This instrument was operated in the passive mode in this series of measurements, i.e., without a sampling pump (2);
4. Dust mass concentration, mg/m^3, and [LLRD], mBq/m^3, from grab-sampling data

were obtained with the nylon cyclones (NC, PADs, open-face filter samplers (OFFS), as well as the cascade impactors. These data appear mostly in tabular form.

It should be noted that the graphs corresponding to item 1, namely MMAD and AMAD graphs, are labelled, Dust: Nat. LLRD where Nat. stands for natural, and LLRD stands, as usual, for Long-Lived Radioactive Dust. The 'label' Nat. LLRD simply indicates that the sampling is done in a natural atmosphere containing LLRD as opposed to 'man-made' dusts injected into the Long-Lived Radioactive Dust Test Facility (LLRDTF) for laboratory work, e.g., AL_2O_3, SiC, talcum, starch and flour, described elsewhere (1). These dusts, in conjunction with the LLRDTF, were used, under laboratory-controlled conditions, to evaluate the dust monitoring instruments used in this study.

The techniques, methodology, and protocols used here for gathering and analyzing data are the same as those amply documented elsewhere (1,2). The instruments evaluated, also used in the characterization of dust, were used in a number of work stations monitoring several mechanical and physico-chemical mill operations, as previously indicated.

The following section presents and discusses at length the experimental data obtained during the instrument evaluation and the LLRD characterization studies. Flow diagrams regarding the milling operations at Cluff Lake and Key Lake are shown in Figures 1 and 2, respectively.

EXPERIMENTAL RESULTS AND DISCUSSION

The experimental results obtained in these studies have been summarized in Tables 1 to 4, Figures 3 to 85, and Figures A1 to A32 of Appendix A, and B1 to B7 of Appendix B. Because of the bulk of data, for the the sake of simplicity, the data will be presented and discussed in several sub-sections.

Of interest in the context of this report are the following observations. Because the experimental work was conducted far (i.e., Saskatchewan) from the laboratory base (i.e., Elliot Lake), and because a great deal of the data of interest are based on precise mass measurements by the cascade impactor (CI) substrates and sampling filters, before and after LLRD exposure, special precautions were taken to ensure that mass measurements would not run into practical difficulties of any kind, such as the lack of an adequate balance of the desired and necessary precision at the experimental site.

For the reasons given above, CI substrates and sampling filters were weighed in Elliot Lake before going into the field and after returning from Saskatchewan. Strictly speaking, this was only a precautionary measure and it is not recommended to rely solely on these mass measurements. The recommended practice is to weigh the samples at the experimental site, provided adequate facilities are available. Fortunately, adequate weighing facilities were available at both mill sites, and hence, on-site measurements (i.e., weighing) could be made of the samples taken. Hence, two sets of results are available, one based on Elliot Lake mass measurements, and another set based on Saskatchewan measurements. In most cases the results differ significantly and this represents a real practical difficulty that the experimenter must face. The problem arises mainly in the handling of the samples during transportation from the experimental site to the laboratory base. Because this basic fact is so often overlooked, it is important to constantly remind the reader of the potentially serious errors that he can incur if adequate precautions are not taken. (One of the major problems is dust shaken off the samples during transportation due to vibration, impaction, and so on).

Unless otherwise specified, the data based on on-site mass measurements will be taken to reflect true experimental conditions. Long-Lived Radioactive Dust activity was measured in Elliot Lake (Ontario). Finally, it should be stressed that the accuracy of the results presented here reflect the substantial difference in average airborne dust concentrations measured at the two mills. Furthermore, although frequent reference to one mill or the other is made in the text, the data for the two mills are discussed concurrently. It should also be noticed that in some cases two different working shifts have been monitored during the same day, usually corresponding to two different mill operations. The following are the dates corresponding to measurements conducted at the two mills, and in the main operations investigated:

Cluff Lake	Feb. 12th	Conveyor transportation
(1991)	Feb. 14th	Milling
	Feb. 15th(1)	Crushing
	Feb. 15th(2)	Yellowcake precipitation
	Feb. 16th	Hopper/ball mill/ conveyor area
Key Lake	Feb. 18th	Crushing/milling (S.A.G.* Mill area)
(1991)	Feb. 19th	Lime slaking
	Feb. 20th	Yellowcake packaging.

The following sub-sections present the data of interest. Again, it should be re-iterated that all the instruments used were placed in the same location, and hence, the differences in the dust characterizations obtained are to be construed to approximately reflect the different characteristics and performance of the various instruments exposed to as nearly equal experimental conditions as was practically possible.

1. MASS MEDIAN AERODYNAMIC DIAMETER (MMAD) AND ACTIVITY MEDIAN AERODYNAMIC DIAMETER (AMAD) DATA

Mass Median Aerodynamic Diameter (MMAD) and AMAD data are shown in Figures 3 to 35. A summary of these data in tabular form is shown in Table 1. The graphs have been grouped chronologically and all correspond to studies conducted during February 1991. The different graphs correspond to the following dates:

---

* stands for Semi Autogeneous Grinder.

Figures 3 to 6 : February 12th (Cluff Lake)
Figures 7 to 10 : February 14th (Cluff Lake)
Figures 11 to 18 : February 15th (Cluff Lake)
Figures 19 to 22 : February 16th (Cluff Lake)
Figures 23 to 26 : February 18th (Key Lake)
Figures 27 to 30 : February 19th (Key Lake)
Figures 31 to 25 : February 20th (Key Lake)

The first and second illustration of each group correspond to the MMAD obtained from data gathered with the Sierra 210 and Marple 290, respectively. The other illustrations in the group correspond to the AMAD obtained by the same instruments in the same order. Data in Table 1 includes results based on field weighing of samples (FW) as well as the same samples weighed at the Elliot Lake Laboratory (ELL). The symbol σ_g stands for geometric standard deviation (GSD in Figures 3 to 35).

Before discussing the data it is important to note that on February 12th, at about 12:45, an electrical power failure occurred that affected the entire mill. The power failure was caused by a fire in one of the four electrical generators in the power house which burned a substantial amount of oil flowing in pipes and produced an extensive oil dust cloud. The above accident had two important effects on the data collected on this day, namely:

a) The instruments which operated on 115 V ceased to function, whereas instrumentation running on battery power packs continued to operate;

b) The airborne burnt oil produced by the fire entered the ventilation system, and from there entered the working locations, therefore being sampled by instrumentation operating on battery power packs. For safety reasons, the buildings were evacuated until it was safe to return. As a result some instruments sampled a great deal of burned oil dust, whereas other instruments such as the Sierra 210 were only partly affected by the accident.

Because of items a) and b), dust data from the Sierra 210 and the Marple 290, obtained on February 12th, cannot be compared although the data are shown in Table 1 and Figures 3 to 6. With the above in mind, Table 1 and Figures 3 to 35 show the following:

1. The MMAD and AMAD data obtained with the Sierra 210 were significantly lower than the data obtained with the Marple 290, i.e., ~54% for the MMAD (from samples weighed in the field, i.e., FW in Table 1), and ~47% for the AMAD. These figures represent average values taking all the data into consideration, excluding some obvious cases such as February 12th in Table 1. It is clear from these data that the Marple 290 over-estimates both the MMAD and AMAD by about 50% relative to the values calculated from data obtained with the Sierra 210.
2. The values for the AMADs obtained with both the Sierra 210 and the Marple 290 were substantially higher (29 to 35%) than the values obtained for the MMAD corresponding to the carrier dust. The relationship of the values for the above variables, represented by the ratio AMAD/MMAD, was 1.35 for the Sierra 210 and 1.29 for the Marple 290. The values, although significantly higher than the values obtained in the past in other experimental work, are in qualitative agreement with the latter and in quantitative agreement with the underground work conducted at Stanleigh Mine (Nov./Dec. 1990) (see ref. 2). The reasons for the AMAD being substantially larger than the MMAD of the carrier dust are not altogether clear. Uncertainties in dust mass determination, as well as α-particle self-absorption effects and other phenomena, are, of course, factors that could play an important role in explaining the discrepancies observed; and
3. The ranges of values for the MMAD and AMAD (excluding February 12th) measured for the two instruments were as follows:

Sierra 210 MMAD : 2.0 μm to 11.4 μm (ave. ~6 μm)
AMAD : 3.0 μm to 17.9 μm (ave. ~8.1 μm)
Marple 290 MMAD : 2.9 μm to 14.6 μm (ave. ~9.2 μm)
AMAD : 5.0 μm to 20.0 μm (ave. ~11.9 μm)

Although the wide ranges of values observed for the MMADs and the AMADs (i.e., ratio of ~5 from maximum to minimum values) are reasonable and consistent with different mechanical and physico-chemical milling operations, the lack of better agreement between the Sierra 210 and the Marple 290 are a cause for serious concern. The results obtained in these two mills indicates that agreement between these two instruments is at best, fair, and at worst, poor.

As anticipated, the largest values for the MMAD and AMAD corresponded to mechanical operations such as yellowcake packaging (Feb. 20th), crushing (cone) (Feb. 15th (1)), and milling (Feb. 18th), and transportation of ore by conveyor belts (Feb. 12th). The values for these variables were significantly higher for these mechanical operations than for physico-chemical operations such as yellowcake precipitation and lime slaking. A summary of these data is given in the Table below:

Location	MMAD (μm)		AMAD (μm)	
	Sierra 210	Marple 290	Sierra 210	Marple 290
Conveyor belt	26.3	36.4	18.6	20.5
Ball mill	5.4	7.9	5.0	9.3
Cone crusher	11.4	14.3	11.6	17.1
Yellowcake prec.	5.6	9.8	8.4	11.2
Ball mill*	8.1	14.6	6.3	11.7
S.A.G. mill	3.4	5.8	4.5	9.2
Lime slaking	2.0	2.9	3.0	5.0
Yellowcake pack.	--	--	17.9	20.0

*Hopper, ball mill, conveyor belt area.

2. DUST MASS AND α-PARTICLE ACTIVITY VERSUS PARTICLE SIZE DISTRIBUTION

The data shown in Figures 3 to 35 are not intuitively easy to interpret. A more readily understandable kind of data are shown in Figures 36 to 67 which give the percentage of dust mass (of the total mass) versus particle cut-off diameter (Figures 36 to 51), or the percentage α-particle activity (of the total activity) versus particle cut-off diameter (Figures 52 to 67). These data were obtained, as before, with the cascade impactors Sierra 210 and Marple 290, and they show similar data as before but presented in a different way. Very often, this type of graph would show an increase in percentage (%) of the total dust mass or α-particle activity versus particle cut-off diameter until a maximum value is attained followed by a decrease in the percentage for the large cut-off diameter end. To a large extent, this is what is observed in some cases (see Figures 38, 42, 46, and 48 for dust mass, and Figures 54, 55 and 58 to 65 for α-particle activity). Naturally, the shape of the graphs depends on the particle size distribution. If the dust cloud has few fineparticle components, the major particle size contribution being in the large particle size range, the graph would show a steady increase in the percentage of mass or α-particle activity with increasing particle size. This is approximately the case for the following graphs tabulated below:

Location	Figure No. % Mass	Figure No. % α-activity	MMAD or AMAD (μm)
Conveyor	36, 37	52, 53	>18
Cone crusher	40, 41	56, 57	>11
Hopper/mill/conv.	44, 45	--	>8
Yellowcake pack.	50, 51	66, 67	>18

In the above table, the first and second figure numbers (for either the % mass or % α-activity column) correspond to the Sierra 210 and Marple 290, respectively. The data shown in the table are consistent with the type of milling operations indicated which are characterized by relatively large MMADs and AMADs, i.e., a large fraction of dust particles is in the large particle size range. In a reduced number of cases, the experimental data showed large inconsistencies, e.g., Figure 43 (yellowcake precipitation), Figure 47 (S.A.G. mill), and Figure 49 (lime slaking). The data shown in these Figures were all obtained with the Marple 290. Because the Sierra 210 results for these operations, and corresponding dates, do not show this behaviour it is concluded that experimental errors and uncertainties are the reasons for the observed data. Weighing uncertainties are high on the list as the potential source of error because of the low dust mass collected by the Marple 290 compared with the mass of the stainless steel substrates used by this instrument.

Close inspection of the data in Figures 36 to 67 suggest that the Sierra 210 'behaves' significantly better than its counterpart, the Marple 290. There is also little doubt that these Figures provide a better 'visualization' of dust characterization than Figures 3 to 35.

Slightly different versions for Figures 36 to 67 are shown in Figures A1 to A20 in Appendix A. These Figures show histograms representing the percentage of dust mass, or α-particle activity, versus particle cut-off diameter as measured from data collected with the Sierra 210 and the Marple 290. The Figures have been arranged in a different way to Figures 36 to 67 for more direct comparison purposes of dust mass or α-particle activity obtained by the two cascade impactors under consideration. Thus, the histograms have been grouped following a specific order for ease of analysis, namely:

a) Percentage dust mass versus cut-off diameter followed by the percentage α-particle activity versus cut-off diameter, both graphs for the Sierra 210, followed by:

b) The same as item a) but for the Marple 290.

The above graph sequence permits easy comparison of dust mass size distribution and α-particle activity distribution for each cascade impactor. With regard to the above, the following items are worth mentioning:

i) Except for some cases, a direct comparison of the dust mass and α-particle activity distributions obtained with either instrument does not suggest a strict correspondence between these two distributions;

ii) In spite of item i), the correspondence between dust mass distribution and α-particle activity distribution is substantially better for the Sierra 210 than for the Marple 290.

Again, the reasons for the discrepancies observed are not clear, but weighing errors and α-particle self-absorption effects are suspected to play a role. This topic will be dealt with in more detail elsewhere.

Concurrent measurements of dust mass concentration and particle size distribution carried out with the automated cascade impactor model QCM PC-2 are somewhat difficult to compare directly with the data obtained with the Sierra 210 and the Marple 290. This is so because, while the data obtained with the latter instruments represent values 'averaged' over relatively long sampling periods, e.g., about 12 hours corresponding to the duration of an entire working shift, the data provided by the QCM PC-2 is of a quasi-instantaneous nature, i.e., the instrument provides readings of dust mass concentration and particle size distribution from air sampled during a few seconds to a few minutes. This high frequency of readings is only possible because of the extreme sensitivity of the instrument. Hence, while this very sensitivity permits the dynamics of dust production of any milling operation to be monitored without difficulty, many measurements are required during a working shift to build a realistic picture of dust characterization and average dust conditions characteristic of a given milling operation. Some of the results obtained with this instrument will be presented and discussed at the end of this section.

Airborne dust mass concentration obtained with the Sierra 210 and Marple 290 (represented, respectively, by [S210] and [M290]), and Long-Lived Radioactive Dust Concentration measured with the same instruments (represented by [LLRD(S210)] and [LLRD(M290)], respectively) are given below:

Date (1991)	Operation	[S210] (mg/m^3)	[M290] (mg/m^3)	[LLRD(S210)] (mBq/m^3)	[LLRD(M290)] (mBq/m^3)
Feb. 12th	Conv. belt	14.70	20.43	2665	3193
Feb. 14th	Milling	0.30	0.50	405	428
Feb. 15th(1)	Crushing	6.81	6.34	904	1193
Feb. 15th(2)	Yellowcake prec.	0.51	0.50	2229	1955
Feb. 16th	H/BM/CB	0.90	0.98	444	703
Feb. 18th	Crushing/milling	0.11	0.15	129	163
Feb. 19th	Lime slaking	0.07	0.08	28	23
Feb. 20th	Yellowcake pack.	0.13	0.09	409	643
	Total:	23:53	29.07	7213	8299

The data tabulated above indicate that the dust mass and [LLRD] measured by the Marple 290 were higher (23% and 15%, respectively) than the values corresponding to the Sierra 210. This is in qualitative agreement with the higher maximum cut-off particle size of the Marple 290 (~21 μm) as compared with the Sierra 210 (~15 μm). Taking this, and experimental errors, into consideration the agreement between these two types of cascade impactors can be considered fairly good. It should also be noted that an agreement of better than 10% (i.e., ~7%) was obtained for the specific activity, in mBq/mg, calculated from data by these two impactors (306 mBq/mg for the Sierra 210 and 286 mBq/mg for the Marple 290). These values are substantially higher than the values obtained during the underground uranium mine tests (~ up to 100 mBq/mg) reported elsewhere (2).

Other data of interest include the ratio of [LLRD] to the dust mass concentration measured with the Sierra 210 and the Marple 290 and denoted, respectively, by: [LLRD(S210)]/[S210] and [LLRD(M290)]/[M290]. These data for the various milling operations monitored are tabulated below:

Date	$\frac{[LLRD(S210)]}{[S210]}$ (mBq/mg)	$\frac{[LLRD(M290)]}{[M290]}$ (mBq/mg)	Ave. (S210 & M290) Specific Activity (mBq/mg)
Feb. 12th	181.3	156.2	168
Feb. 14th	1350.0	854.0	1102
Feb. 15th(1)	132.7	188.2	160
Feb. 15th(2)	4370.6	3910.0	4140
Feb. 16th	493.3	717.3	605
Feb. 18th	1172.7	1086.7	1130
Feb. 19th	400.0	287.5	343
Feb. 20th	3146.1	7144.4	5145

The data presented above agree with what one would expect on basic principles and theoretical arguments, namely, dusts generated in the final stages of the milling cycle, such as yellowcake precipitation (Feb. 15th (2)), and naturally, yellowcake packaging (Feb. 20th) have the highest specific activity, SA. A similar reasoning suggests that the lowest values for the SA should be measured for the initial mechanical stages of the milling cycles, e.g., ore crushing, Feb. 15th(1), and ore transportation, Feb. 12th. Intermediate stages in the cycle show correspondingly intermediate values for the specific activity, e.g., milling (Feb. 14th and 18th).

It is not difficult to see that the variation in specific activity through the different stages of the milling cycle is related to:

a) progressive refinement of the ore, i.e., progressive enrichment of the dust particles in U-compounds;

b) particle size distribution of the dust cloud, or more specifically, the value of the MMAD, and hence AMAD, which varies with the milling operation; and

c) α-particle self-absorption effects in the U-containing dust.

As is well known, the initial (mechanical) stages of the milling cycle, such as crushing and ore transportation, are characterized by large particle sizes. Furthermore, no refinement of any kind has yet taken place. Hence, the specific activity for these large, not 'enriched' dust particles should be expected to be low. The opposite holds true for the physico-chemical operations of the cycle such as yellowcake extraction, yellowcake precipitation, and the final mechanical operation of the cycle, yellowcake packaging.

The data discussed in this section agree with experimental expectations. The last part of this section is devoted to a brief presentation of the results obtained with the automated cascade impactor QCM PC-2.

A summary of the data obtained with the QCM PC-2 is shown in Figures 68 to 76 for the eight working shifts monitored at Cluff Lake and Key Lake. These Figures show the particle size distribution and the dust mass concentration (print-out) obtained within each particle size range, as well as the total dust mass concentration. As previously indicated, the QCM PC-2 is a 10-stage cascade impactor with the following particle cut-off sizes ($D_{P,50}$) in μm:

Stage No.	$D_{P,50}$ (μm)
1	25.0
2	12.5
3	6.4
4	3.2
5	1.6
6	0.8
7	0.4
8	0.2
9	0.1
10	0.05

Each figure shows three complete measurements taken at three different times during the working shift. The substantial variability in both particle size distribution and dust mass concentration during each shift is quite apparent and faithfully reflects varying dust conditions during the particular milling operation monitored. The range of concentration values (minimum and maximum) are tabulated below:

Date (1991)	Operation	[QCM PC-2] (mg/m^3)	Time
Feb. 12th	Conveyor belt	0.37-1.60	9:56-12:16
Feb. 14th	Milling	0.07-0.14	20:00-23:53
Feb. 15th(1)	Crushing	0.03-0.91	9:22-13:21
Feb. 15th(2)	Yellowcake prec.	0.08-0.19	22:46-0:02 (Feb. 16th)
Feb. 16th	H/BM/CB	0.05-0.14	~10:00-12:00 (?)
Feb. 18th	Crushing/milling	0.01-0.02	10:00-14:00
Feb. 19th	Lime slaking	0.02-0.16	10:00-24:00
Feb. 20th	Yellowcake pack.	0.02-0.07	9:00-14:00

The above operations were monitored intermittently during each working shift. Except for one shift, intermittent measurements were extended over a period of 2 to 5 h. It can be seen from the above table that:

a) The dust mass concentrations were significantly lower for the Key Lake operation (Feb. 18th to Feb. 20th) than for the Cluff Lake operation (Feb. 12th to Feb. 16th).

b) The highest values for the mass concentration were attained for the ore crushing and ore transportation operations, as expected, and in qualitative agreement with data for the Sierra 210 and Marple 290 discussed previously. (It should be noted, as indicated earlier, that by conveyor belt is to be understood as monitoring at the ore loading zone/conveyor belt transfer point.)

As has already been pointed-out, straightforward comparison between intermittent measurements conducted with the QCM PC-2 and 'integrated long-term' measurements, carried out with the Sierra 210 and the Marple 290 over a complete working shift of 12 h, cannot easily be made. The reasons for this have been indicated above. Although a reasonable agreement can still be inferred, the data for the QCM PC-2 on Feb. 12th and Feb. 15th(1) are about an order of magnitude lower than the figures obtained with the other two cascade impactors. For Feb. 12th, the day of the fire, and hence the failure of the ventilation system, a satisfactory explanation can be found:

a) The last measurement made with the QCM PC-2 was at about 12:16, i.e., approximately 30 min before the power failure, and hence, failure of the ventilation system;

b) In spite of the power failure, the Marple 290, owing to its independent power supply, continued to sample for about two more hours until the power was turned off manually by the operator;

c) Although the main power failure automatically turned off the sampling pump of the Sierra 210, a large amount of soot, caused by the fire, and mineral dust had already been sampled by the instrument prior to the actual failure of the ventilation system.

Items a) to c) are the main reasons for the discrepancies observed between the data obtained by the Sierra 210 and the Marple 290, on one hand, and the QCM PC-2 on the other hand. As for Feb. 15th (1) (Cone crushing operation), the QCM PC-2 was only operated during the morning and during periods of non-maximum dust loading to avoid saturation of the QCM delicate piezoelectric crystal system.

However, in spite of the above difficulties, the data obtained by the QCM PC-2 agree qualitatively with that obtained with the Sierra 210 and Marple 290. From the quantitative standpoint, one should consider the basic differences and conceptual approaches that differentiate long-term average sampling techniques from instantaneous measurements. The only way to reconcile these two basically different approaches is by making many instantaneous measurements and averaging these measurements to compare the results with data obtained with long sampling-time averaging instrumentation. Both methods have advantages and disadvantages over one another, and the choice of method is related to the specific purpose of the measurement.

The particle size distribution data shown in Figures 68 to 76 obtained with the QCM PC-2 can be compared with the corresponding graphs given in Appendix A for the other two cascade impactors. The result of this comparison is rather disappointing, while most of the dust mass-particle size distribution (~80%) is recorded by the QCM PC-2 in the approximate particle size range 1-6 μm, a relatively large percentage (>30%) of the mass-size distribution is found at particle sizes ≥9 μm. However, the same, or similar, considerations discussed above apply equally well to the particle size distributions.

Finally, analyses of particle size distribution for the milling operations monitored were conducted using Optical Particle Counter (OPC) model CLIMET model CI-7300. However, because this instrument does not give information on dust mass distribution or dust mass (as all or part of the other instruments evaluated here) but provides particle size distribution by particle size number, it is felt that a discussion on the results obtained with this instrument is best done separately from the main body of this report. Such a discussion is presented in Appendix B.

3. DUST MASS CONCENTRATION MEASURED USING THE MINIRAM MODEL PDM-3

From all the instruments used for dust mass characterization in the U-mills monitored, the MiniRam PDM-3 was the only one of a continuous type, i.e., provides dust concentration data continuously at 1 min intervals. This instrument, therefore, permits the study of the presence of airborne dust in the respirable size range in the mills as a function of time. Hence, dust quantification of different milling operations that either generate dust or remove it from the air is possible.

Figures 77 to 85 show the dust mass concentration versus time for the milling operations monitored. Also shown in these graphs are the averages of the mass concentrations over the entire shifts indicated by solid horizontal lines. The averages of these mass concentrations are also given in Table 2. Figures 77 to 85 show the great variability in dust concentration during the shift, i.e., variations of up to an order of magnitude can be observed. Variations by a factor of 2 to 5 were quite common, as the above graphs indicate.

There are a number of reasons that can account, in most cases, for the variability observed, namely:

a) Variations in the feeding rate in a particular milling operation;
b) Initiation or interruption of a given milling operation;
c) Interference of nearby milling operations on the operation under monitoring;
d) Changes in airflow rate;
e) Wetting and cleaning of machinery and installations, and so on.

Therefore, in view of the above, it is not surprising to also observe variability in the particle size distributions. Because of particle size range and upper particle size cut-off considerations, the only instrument that the MiniRam can meaningfully be compared with is the nylon cyclone (NC). But even in this case, the dust characteristics of these two instruments differ sufficiently enough to make a direct comparison difficult. The other instruments, namely the cascade impactors (Sierra 210 and Marple 290) and the open face filter sampler (OFFS), should give significantly higher dust mass concentration values because of their much wider particle size range characteristics. The values obtained for the average dust mass concentrations obtained with the MiniRam PDM-3, [PDM-3], and the nylon cyclone, [NC], are tabulated below. A discussion of the performance of the NC and OFFS will follow:

Date (1991)	Operation	[PDM-3] (mg/m^3)	[NC] (mg/m^3)	Remarks
Feb. 12th	Conveyor belt	0.27	2.88	See Figure 77
Feb. 14th	Milling	0.09	0.08	--
Feb. 15th(1)	Crushing	0.20	0.59	See Figure 79
Feb. 15th(2)	Yellowcake prec.	0.07	0.07	--
Feb. 16th	H/BM/CB	0.09	0.10	--
Feb. 18th	Crushing/milling	0.04	0.04	--
Feb. 19th	Lime slaking	0.04	0.03	--
Feb. 20th	Yellowcake pack.	0.06	0.06	--

The table above shows good agreement between the values for [PDM-3] and [NC] except for two operations (shifts), namely, Feb. 12th (ore transportation at the conveyor belt/ore loading transfer point), and Feb. 15th for the crushing operation. The first case can easily be explained because dust monitoring by the MiniRam stopped at about 12:30 (see Figure 77), shortly before the fire, and hence, failure of the ventilation system due to a general electrical power failure. However, the nylon cyclones continued to operate for a substantially longer time, and hence, during the period of heavy dust and soot deposition caused by the fire.

For the crushing operation (Feb. 15th (1)), the nylon cyclones give values for the dust concentration three times larger than the values obtained for the average concentration calculated from the MiniRam PDM-3 data. (See Table above and Figure 79.) There is no obvious explanation for this discrepancy nor record of instrument malfunction. Hence, apart from this shift, the agreement between the nylon cyclones and the MiniRam can be considered fairly good. Finally, the values measured by the instrument ranged from ~0.02 mg/m^3 to >0.5 mg/m^3. The average daily values were in the range 0.04 mg/m^3 to ~0.3 mg/m^3 (see table).

4. DUST AND LLRD CONCENTRATION CALCULATED FROM PAD'S DATA

The personal α-particle dosimeters (PADs) were used at Cluff Lake where they monitored the same milling operations as the rest of the instrumentation evaluated. The PADs were not used at Key Lake, mainly for the following reasons:

a) These devices were not used by the Key Lake personnel as part of their radioactivity environmental program, and hence, there were no battery chargers available to recharge the instruments after the working shift;

b) The Long-Lived Radioactive Dust concentration, [LLRD], was, in general, significantly lower at Key Lake than at Cluff Lake;

c) The total monitoring time available at Key Lake was rather short, a problem which compounded with item b), and which would have made accurate analysis of the data rather difficult.

The sampling period at Cluff Lake lasted for four working shifts (Feb. 14th, Feb. 15th (1), Feb. 15th (2), and Feb. 16th), totalling 40.23 hours. Because of the fire on Feb. 12th, the data for this shift were analyzed independently. Two PADs were used in the evaluation. Hence, two sampling runs were done, namely, a ~12 h period on Feb. 12th, and a ~40 h period for the other 4 working shifts indicated above.

The dust collection characteristics of the PADs are not known well enough to categorize these devices for the purpose of comparison with other instrumentation. Because the PADs undoubtedly have some particle size selection capabilities, their response must lie somewhere between the open face filter sampler (OFFS) and the nylon cyclone (NC). The table below shows a comparison between the PADs, the OFFS and the NC. Also shown for reference purposes is data pertaining to the Sierra 210. The concentrations have been averaged over the same period as the total sampling time corresponding to the PADs. When more than one instrument of a given type has been used, e.g., PAD's, NC, etc., the average value for the several instruments of the same type is quoted. (The square brackets are used, as usual, to indicate concentration.)

Sampling Period, 1991	[NC] (mg/m^3)	[PAD] (mg/m^3)	[OFFS] (mg/m^3)	[S210] (mg/m^3)
Feb. 12th	2.88	11.80	9.18	14.7
Feb. 14th to 16th	0.2	3.40	1.86	2.1

Data regarding the long-lived α-particle activity associated with the above samples are given below.

Sampling Period, 1991	[LLRD(NC)] (mBq/m^3)	[LLRD(PAD)] (mBq/m^3)	[LLRD(OFFS)] (mBq/m^3)	[LLRD(S210)] (mBq/m^3)
Feb. 12th	284	1310	594	2665
Feb. 14th to 16th	92.5	673.5	1147	995.5

The first table shows that the dust concentrations measured by the PADs are substantially higher than those obtained with the NC and OFFS. This rather unexpected result has also been reported elsewhere (2), where a series of field tests in an underground U-mine showed similar results.

The long-lived radioactivity data shown in the second table suggests that [LLRD(PAD)] is more in accordance with what one would expect to be the case for dust alone, i.e., [PAD] somewhere in between [NC] and [OFFS]. The data for Feb. 12th are somewhat uncertain because of the high soot concentration generated during the fire, and hence, potentially large α-particle self-absorption effects. The specific activities shown in the table below provide additional help in the interpretation of the results. (As previously indicated, the specific activity, SA, is defined by the ratio SA = [LLRD(X)]/[X], where X refers to the specific type of instrument under consideration.)

Sampling Period, 1991	SA(NC) (mBq/mg)	SA(PAD) (mBq/mg)	SA(OFFS) (mBq/mg)	SA(S210) (mBq/mg)
Feb. 12th	98.6	111	64.6	181
Feb. 14th to 16th	462.5	198	617	474

As the above table indicates, the values for the SA corresponding to the first sampling period (Feb. 12th) are substantially lower than the values obtained for the second sampling period (4 working shifts). This is consistent with the large amount of soot generated during the fire and which has few long-lived radioactive materials associated with it. In contrast with the first sampling period, the second period shows much higher long-lived radioactivity associated with the dust indicating the presence of ^{226}Ra, ^{238}U, and other long-lived radionuclides.

The higher than 'normal' dust concentration measured by the PAD is rather puzzling and it is suspected to be related with the particle size selection characteristics of the device, which in turn are related to the geometry of the sampling head, the sampling airflow rate, and the airflow patterns generated around the sampling head by the 'turbine' pump used in the instrument. It is possible that the PAD is particularly efficient in collecting particles of size larger (heavier) than other instruments which could account for the higher values observed for the concentrations measured. At this stage, however, this is purely speculative and requires verification. In any case, it would be desirable to investigate the particle size collection characteristics of this device if it is to be used as a LLRD monitor, in addition to being used as a radon progeny and thoron progeny monitor for personal radiation exposure purposes.

5. OPEN-FACE FILTER SAMPLER (OFFS) AND NYLON CYCLONES (NC) DATA

Because of the size cut-off of the NCs, devices designed for estimating respirable dust concentration for occupational hygiene and regulatory purposes, the dust concentration measured by these devices should be lower than the concentration measured by the OFFS. The same applies when comparing the NCs with the cascade impactors, devices that have a much higher size cut-off, i.e., >15 μm, depending on operating airflow rate conditions. Concentration measurements carried out with the NCs and OFFS are shown in the Table below, which also shows data for the cascade impactors and MiniRam PDM-3 for comparison purposes.

Date (1991)	[OFFS] (mg/m^3)	[NC] (mg/m^3)	[S210] (mg/m^3)	[M290] (mg/m^3)	[PDM-3] (mg/m^3)
Feb. 12th	9.18	2.88	14.70	20.43	0.27
Feb. 14th	0.38	0.08	0.30	0.50	0.09
Feb. 15th(1)	6.02	0.59	6.81	6.34	0.20
Feb. 15th(2)	0.51	0.07	0.51	0.53	0.07
Feb. 16th	0.67	0.10	0.90	0.98	0.09
Feb. 18th	0.06	0.04	0.11	0.15	0.04
Feb. 19th	0.05	0.03	0.07	0.08	0.04
Feb. 20th	0.15	0.06	0.13	0.09	0.06

The above table shows that, indeed, the values obtained with the nylon cyclones, NC, are lower than those obtained with the OFFS and the cascade impactors Sierra 210 and Marple 290. Furthermore, the values obtained for the OFFS are somewhat lower than those for the cascade impactors. If the results for Feb. 12th are not taken into consideration, and the mass concentrations are averaged over the entire monitoring period, the agreement between the OFFS and the cascade impactors is within 12% with the latter having values slightly higher (~12%) than the values obtained for the former. If the results are averaged for the two mills independently, the concentrations measured by the cascade impactors are about 12% higher than the

OFFS values obtained for Cluff Lake and about 22% higher than the OFFS values for Key Lake. The higher difference found in the latter case could tentatively be ascribed to the larger measuring errors associated with mass determination at the Key Lake facilities where dust mass concentrations were substantially lower (i.e., by a factor of 20 according to the OFFS and cascade impactors) than at the Cluff Lake facilities. It is worth noting that while the concentration ratios between Cluff Lake and Key Lake as measured with the OFFS, the Sierra 210, and the Marple 290 were, respectively, 21.8, 21.3 and 19, the ratio for the nylon cyclones was only 5.25. This would seem to suggest that a large fraction of the airborne dust is in the respirable size range to which the NC is particularly sensitive.

The Long-Lived Radioactive Dust concentration, [LLRD], and the specific activity, SA, obtained with the above instruments are given in the next two tables, respectively.

Date (1991)	[LLRD(OFFS)] (mBq/m^3)	[LLRD(NC)] (mBq/m^3)	[LLRD(S210)] (mBq/m^3)	[LLRD(M290)] (mBq/m^3)
Feb. 12th	594	284	2665	3193
Feb. 14th	474	86	405	428
Feb. 15th(1)	1245	108	904	1193
Feb. 15th(2)	2419	136	2229	1955
Feb. 16th	452	40	444	703
Feb. 18th	116	19	129	163
Feb. 19th	19	5	28	23
Feb. 20th	782	17	409	643

Date (1991)	SA(OFFS) (mBq/mg)	SA(NC) (mBq/mg)	SA(S210) (mBq/mg)	SA(M290) (mBq/mg)
Feb. 12th	65	99	181	156
Feb. 14th	1247	1075	1350	856
Feb. 15th(1)	207	183	133	188
Feb. 15th(2)	4743	1943	4370	3689
Feb. 16th	675	400	493	717
Feb. 18th	1933	475	1173	1087
Feb. 19th	380	167	400	287
Feb. 20th	5213	283	3146	7144

Similar considerations as before show the following:

a) The [LLRD(OFFS)] > [LLRD(NC)]. Furthermore, [LLRD(OFFS)] ~ [LLRD(S210)] ~ [LLRD(M290)]. These conditions hold true for Cluff Lake and are within ~40% for Key Lake, where data are somewhat less accurate for the reasons already stated. The overall agreement, i.e., Cluff Lake and Key Lake (average of both), is within about 20%;

b) Similar considerations and conclusions as in item a) apply equally well to the case of the specific activities, SA;

c) As expected, the SA was largest for the yellowcake packaging (Feb. 20th), followed by the yellowcake precipitation operation (Feb. 15th(2)), the crushing/milling operation (Feb. 18th), and the milling operation (Feb. 14th). An exception to this was for the nylon cyclone data at Key Lake where the SA for the crushing/milling operation (Feb. 18th) was higher than the SA for the yellowcake packaging operation (Feb. 20th). This result is most probably related to the low values obtained for [NC] and [LLRD(NC)] in this mill. Low concentration measurements are more susceptible to errors, and hence, inherently less accurate than either higher concentration measurements or measurements conducted with more sensitive instrumentation, or instrumentation responsive to a wider particle size range.

COMPARISON OF DATA OBTAINED WITH THE DIFFERENT INSTRUMENTS USED

A summary of the data obtained with the various instruments evaluated in the U-mills where dust characterization measurements were conducted is presented in Table 3 (dust mass concentration), and Table 4 (Long-Lived Radioactive Dust concentration). These tables show some items worth mentioning.

1. Dust mass concentration levels and Long-Lived Radioactive Dust concentrations, [LLRD], were much lower at Key Lake than at Cluff Lake;

2. The highest values for the above variables were measured using the Open Face Filter Samplers (OFFS), and the manual (mechanical) cascade impactors Sierra 210 and Marple 290. The values measured by these instruments were, in general, substantially higher than the values obtained with the MiniRam PDM-3, and the nylon cyclones (NC). This is understandable because the latter are only sensitive in the respirable particle size range, whereas the other above-mentioned instruments respond to particle sizes >15 to 25 μm, depending on airflow rate conditions;
3. The PADS gave values for [PAD] higher than expected (2), and values for [LLRD(PAD)] lower than anticipated. Alpha-particle self-absorption effects should not be ruled out as, at least, partially responsible for the latter result;
4. The intermittent measurements conducted with the QCM PC-2 are found to be in partial agreement (depending on the operation monitored, the frequency of measurements, and the history of the operation) with data obtained with both the MiniRam PDM-3 and the nylon cyclones on one hand, and the cascade impactors of the 'manual' type used (Sierra 210 and Marple 290), on the other hand. Some suggestions and plausible explanations to shed light on these discrepancies have been offered.

From the discussions in this report, one may surmise that agreement between the instruments used to characterize dust at the two mills is reasonably fair in a number of cases if allowance is made for the:

a) different characteristics of each instrument used, such as particle size range and size cut-off;
b) extremely variable field conditions encountered for any given milling operation;
c) diversity of milling operations monitored;
d) mutual interference (shadow effects, and so on) of the different instruments used; and

e) slightly different locations where the instruments had to be placed in order to avoid item d).

The data in this report are only a fraction of all the data obtained in the course of several related studies. In other reports, data obtained under laboratory-controlled conditions and in one underground uranium mine have been presented and discussed (2). General conclusions and recommendations on LLRD characterization and instrument evaluation will be deferred to a special summing-up report.

ACKNOWLEDGEMENT

The authors would like to thank E. Edwardson for assisting in some aspects of this project.

REFERENCES

1. Bigu, J., "Radioactive dust sampling. Part 1 - Laboratory test facilities and sampling instrumentation used"; Report in compliance with AECB Contract No. 4.108.1, entitled "Comparison of Radioactive Aerosol Sampling Instruments"; phase 2, part 1, 1991.

2. Bigu, J., "Radioactive dust sampling. Part 3 - Long-Lived Radioactive Dust (LLRD) characterization and LLRD instrument evaluation in an underground uranium mine"; Report in compliance with AECB Contract No. 4.108.1, entitled "Comparison of Radioactive Aerosol Sampling Instruments"; phase 2, part 3, 1991.

Table 1 - MMAD, AMAD and σ_g for Feb. 12th to 20th, 1991 (Saskatchewan field work).

Instrument	Date (1991)	Substrate Material	Type of Dust	MMAD (um) (FW)	Mass Og (FW)	MMAD (um) (ELW)	Mass Og (ELW)	AMAD (um)	Activity Og	Remarks
Sierra 210	Feb. 12	GF	Cluff Lake	26.280	4.160	17.600	2.786	18.569	4.350	
Marple 290A	Feb. 12	SS	Cluff Lake	51.988	8.724	52.590	9.350	20.483	1.913	MMAD & mass Og exclude last pt
Marple 290B	Feb. 12	SS	Cluff Lake	36.380	7.410	33.908	6.711	20.483	1.913	MMAD & mass Og for all points
Sierra 210	Feb. 14	GF	Cluff Lake	5.390	4.340	6.552	3.549	5.041	3.428	
Marple 290	Feb. 14	SS	Cluff Lake	7.940	5.380	8.833	4.636	9.300	2.04\2.8	
Sierra 210	Feb. 15 (1)	GF	Cluff Lake	11.450	3.020	9.782	2.699	11.634	3.416	
Marple 290	Feb. 15 (1)	SS	Cluff Lake	14.290	2.960	14.166	3.076	17.100	2.670	
Sierra 210	Feb. 15 (2)	GF	Cluff Lake	5.640	3.270	6.247	2.901	8.357	3.187	
Marple 290A	Feb. 15 (2)	SS	Cluff Lake	9.760	1.770	9.800	2.781	100.129	2.112	straight line
Marple 290B	Feb. 15 (2)	SS	Cluff Lake	9.760	1.770	9.800	2.781	11.200	2.31\1.92	curved line
Sierra 210	Feb. 16	GF	Cluff Lake	8.070	3.830	7.970	3.327	6.342	3.044	
Marple 290	Feb. 16	SS	Cluff Lake	14.630	3.630	19.548	3.677	11.700	2.720	
Sierra 210	Feb. 18	GF	Key Lake	3.380	5.280	3.689	5.287	4.479	3.681	
Marple 290	Feb. 18	SS	Key Lake	5.770	11.050	10.094	2.328	9.200	1.96\2.88	
Sierra 210	Feb. 19	GF	Key Lake	2.010	4.530	1.951	7.327	2.996	4.294	
Marple 290	Feb. 19	SS	Key Lake	2.920	3.390	12.430	4.702	5.000	3.040	
Sierra 210	Feb. 20	GF	Key Lake	0.750	36.480	0.771	117.507	17.864	3.685	
Marple 290	Feb. 20	SS	Key Lake					20.000	2.200	

GF = glass fibre
SS = stainless steel
FW = field weight
ELW = Elliot Lake Weight

Table 2 - MiniRam daily averages - Cluff Lake/Key Lake

Date (1991)	Time	Daily Ave. (mg/m^3)	Comments
Feb. 12th	10:30-12:20	0.268	MiniRam digital printout 1 min average every 10 min.
Feb. 14th	08:24-16:44	0.093	MiniRam digital printout 1 min average every 10 min.
Feb. 15th(1)	10:27-18:37	0.200	MiniRam digital printout 1 min average every 10 min.
Feb. 15th(2)	23:06-07:26	0.071	MiniRam digital printout 1 min average every 10 min.
Feb. 16th	10:01-19:41	0.087	MiniRam digital printout 1 min average every 10 min.
Feb. 18th	09:59-02:19	0.041	MiniRam digital printout 1 min average every 10 min.
Feb. 19th	10:11-14:31	0.041	MiniRam digital printout 1 min average every 10 min.
Feb. 20th	08:51-17:10	0.061	MiniRam digital printout 1 min average every 10 min.
Feb. 21st	09:00-17:10	0.088	MiniRam digital printout 1 min average every 10 min.

Table 3 - Summary of dust mass concentration measured by different instruments

Date (1991)	Operation	[OFFS] (mg/m^3)	[NC] (mg/m^3)	[S210] (mg/m^3)	[M290] (mg/m^3)	[PDM-3] (mg/m^3)	[QCM] (mg/m^3)	[PAD] (mg/m^3)	Remarks
Feb. 12th	Conveyor belt	9.18	2.88	14.70	20.43	0.27	0.37-1.60	11.8	Cluff Lake
Feb. 14th	Milling	0.38	0.08	0.30	0.50	0.09	0.07-0.14	3.4	" "
Feb. 15th(1)	Crushing	6.02	0.59	6.81	6.34	0.20	0.03-0.91		" "
Feb. 15th(2)	Yellowcake prec.	0.51	0.07	0.51	0.53	0.07	0.08-0.19		" "
Feb. 16th	H/BM/CB	0.67	0.10	0.90	0.98	0.09	0.05-0.14		" "
Feb. 18th	Crushing/milling	0.06	0.04	0.11	0.15	0.04	0.01-0.02	--	Key Lake
Feb. 19th	Lime slaking	0.05	0.03	0.07	0.08	0.04	0.02-0.16	--	" "
Feb. 20th	Yellowcake pack.	0.15	0.06	0.13	0.09	0.06	0.02-0.07	--	" "

Table 4 - Summary of Long-Lived Radioactive Dust concentration, [LLRD], measured by different instruments

Date (1991)	Operation	OFFS (mBq/m^3)	NC (mBq/m^3)	S210 (mBq/m^3)	M290 (mBq/m^3)	PAD (mBq/m^3)	Remarks
Feb. 12th	Conveyor belt	594	284	2265	3192	1310	Cluff Lake
Feb. 14th	Milling	474	86	405	427	673	" "
Feb. 15th(1)	Crushing	1245	108	904	1193		" "
Feb. 15th(2)	Yellowcake prec.	2419	136	2229	1955		" "
Feb. 16th	H/BM/CB	452	40	444	703		" "
Feb. 18th	Crushing/Milling	116	19	129	163	--	Key Lake
Feb. 19th	Lime slaking	19	5	28	23	--	" "
Feb. 20th	Yellowcake pack.	782	17	409	643	--	" "

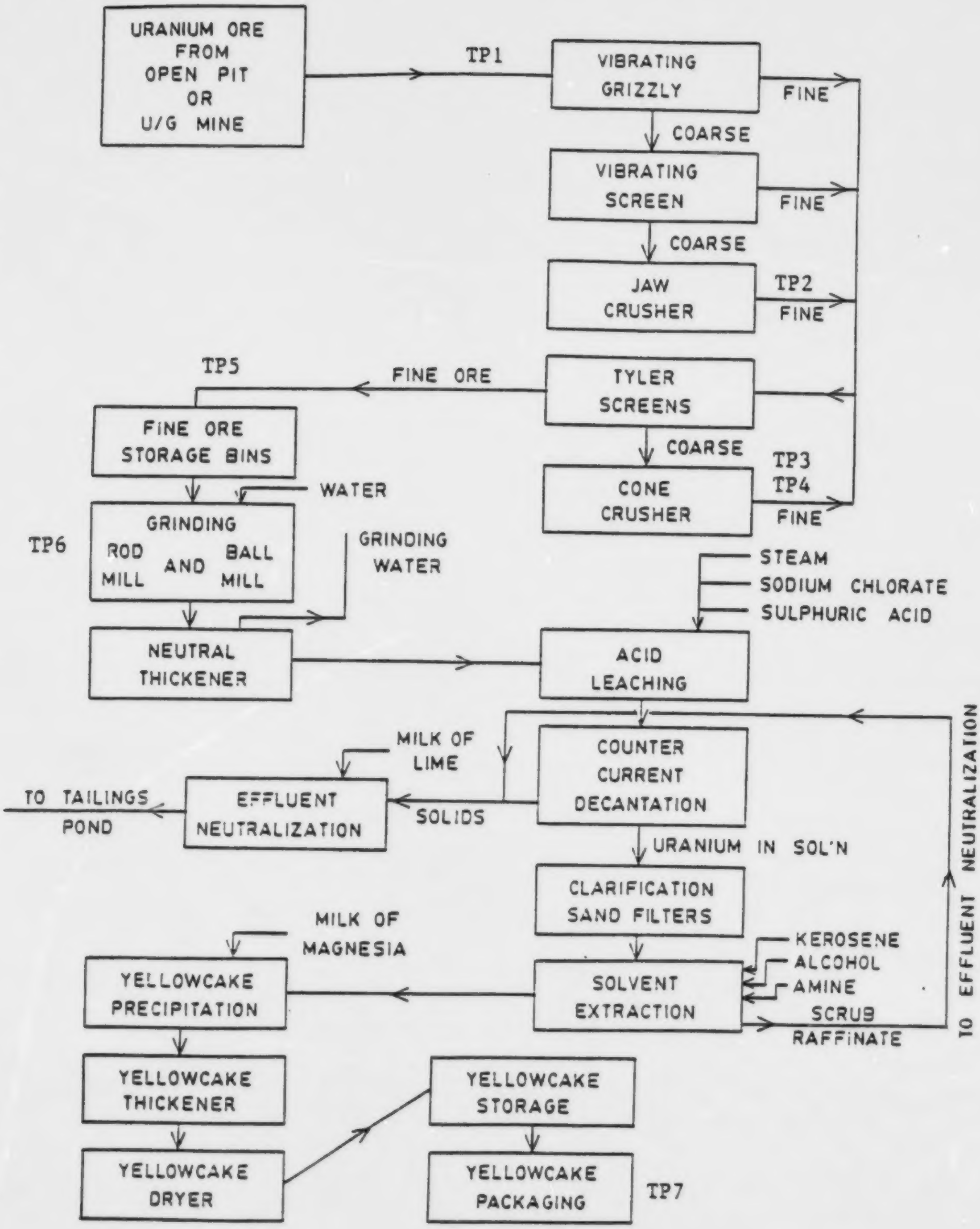

URANIUM ORE FROM OPEN PIT OR U/G MINE
TP1
VIBRATING GRIZZLY
FINE
COARSE
VIBRATING SCREEN
FINE
COARSE
JAW CRUSHER
TP2
FINE
TP5
FINE ORE
TYLER SCREENS
FINE ORE STORAGE BINS
COARSE
TP3
TP4
CONE CRUSHER
FINE
WATER
GRINDING ROD MILL AND BALL MILL
TP6
GRINDING WATER
STEAM
SODIUM CHLORATE
SULPHURIC ACID
NEUTRAL THICKENER
ACID LEACHING
MILK OF LIME
COUNTER CURRENT DECANTATION
TO TAILINGS POND
EFFLUENT NEUTRALIZATION
SOLIDS
URANIUM IN SOL'N
CLARIFICATION SAND FILTERS
TO EFFLUENT NEUTRALIZATION
MILK OF MAGNESIA
KEROSENE
ALCOHOL
AMINE
YELLOWCAKE PRECIPITATION
SOLVENT EXTRACTION
SCRUB RAFFINATE
YELLOWCAKE THICKENER
YELLOWCAKE STORAGE
YELLOWCAKE DRYER
YELLOWCAKE PACKAGING
TP7

Fig. 1 - Mill process flowsheet for Cluff Lake.

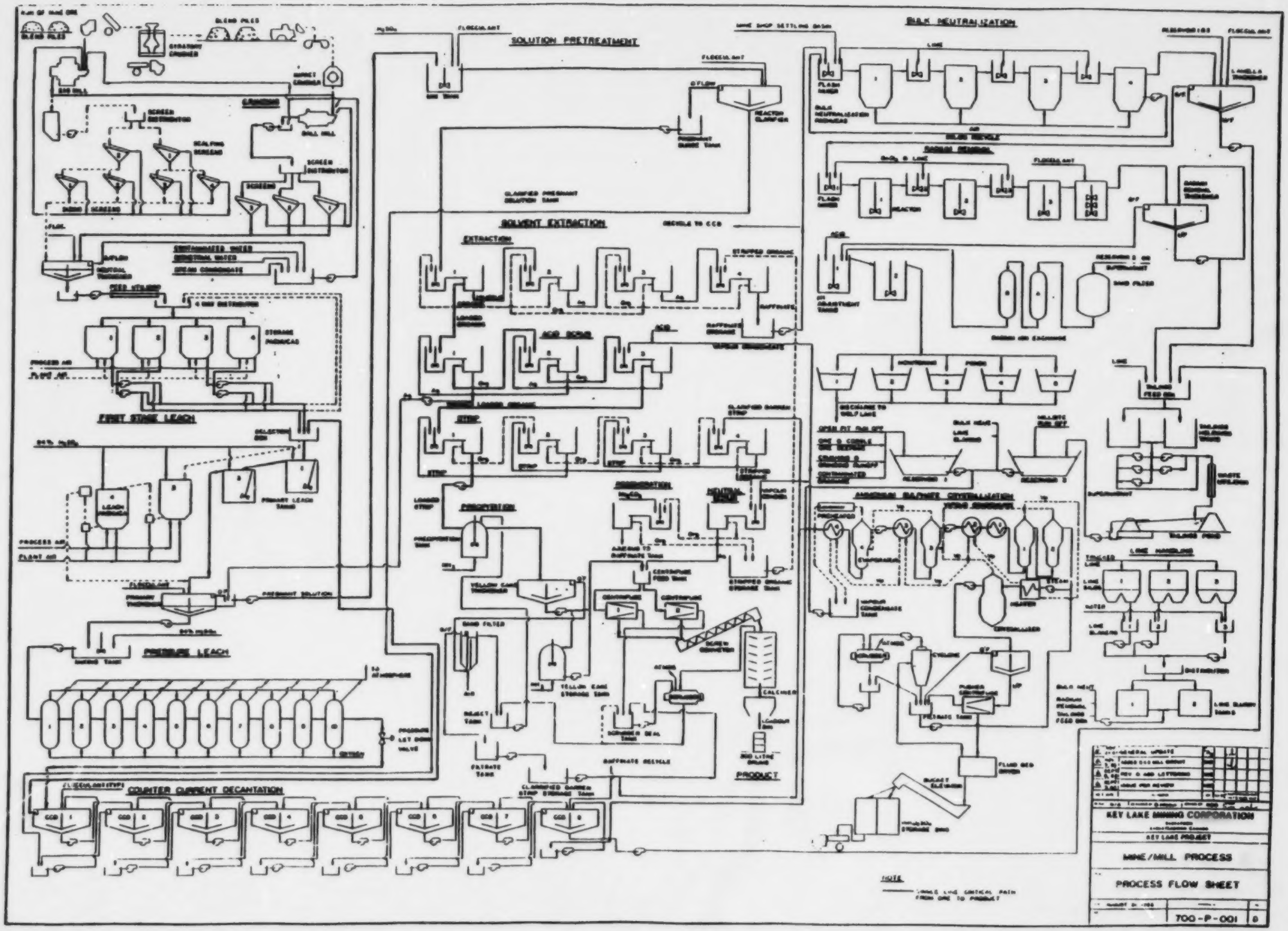

SOLUTION PRETREATMENT
BULK NEUTRALIZATION
GRINDING
SOLVENT EXTRACTION
EXTRACTION
ACID SCRUB
STRIP
FIRST STAGE LEACH
PRECIPITATION
REGENERATION
PRESSURE LEACH
COUNTER CURRENT DECANTATION
PRODUCT
LIME HANDLING
CALCINER
PRESSURE LET DOWN VALVE
FILTRATE TANK
NOTE
KEY LAKE MINING CORPORATION
KEY LAKE PROJECT
MINE/MILL PROCESS
PROCESS FLOW SHEET
700-P-001

Fig. 2 - Mill process flowsheet for Key Lake.

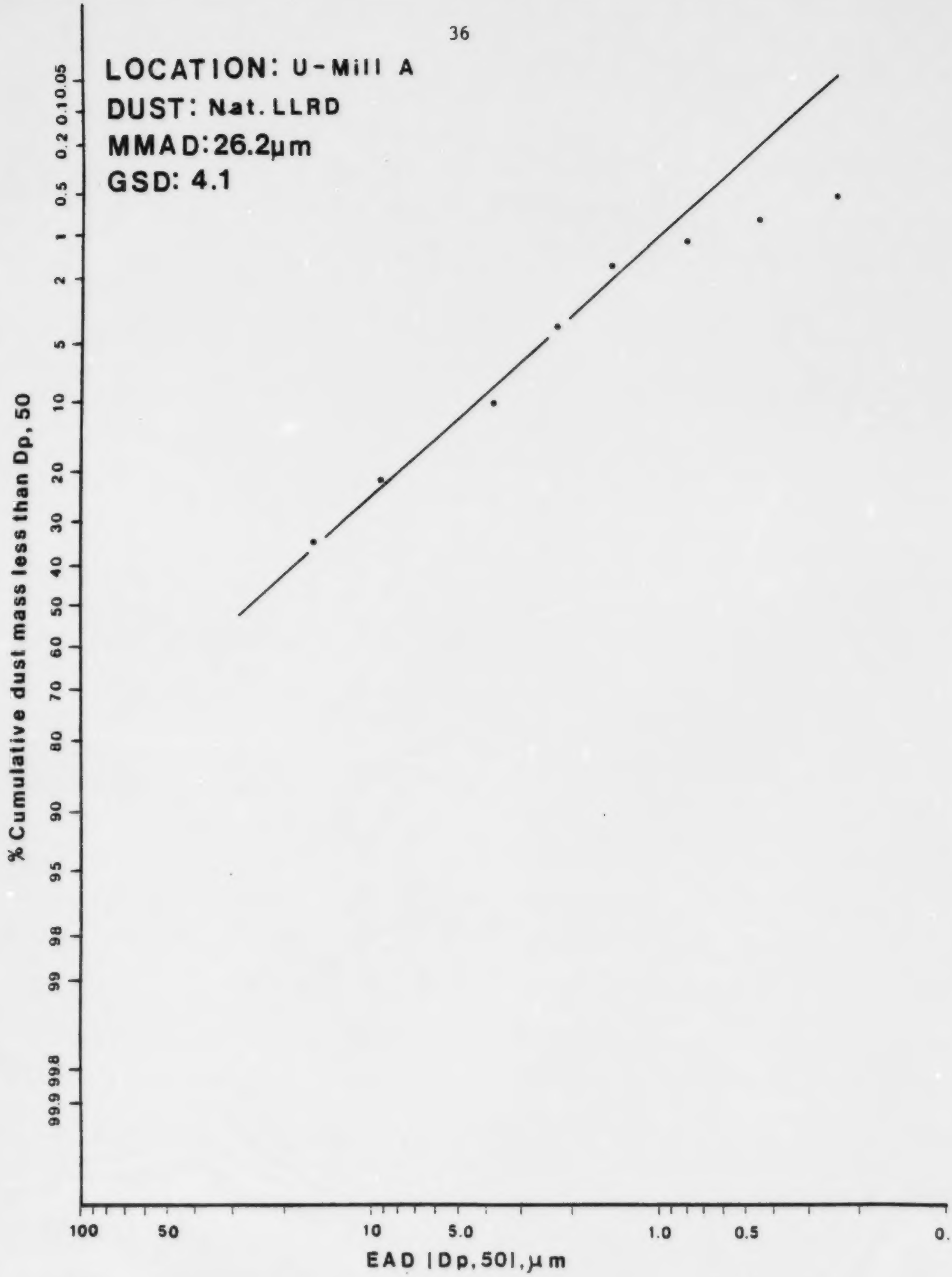


Fig. 3 - Percentage cumulative dust mass versus EAD measured with the Sierra 210 at the crusher/conveyor belt transfer point.

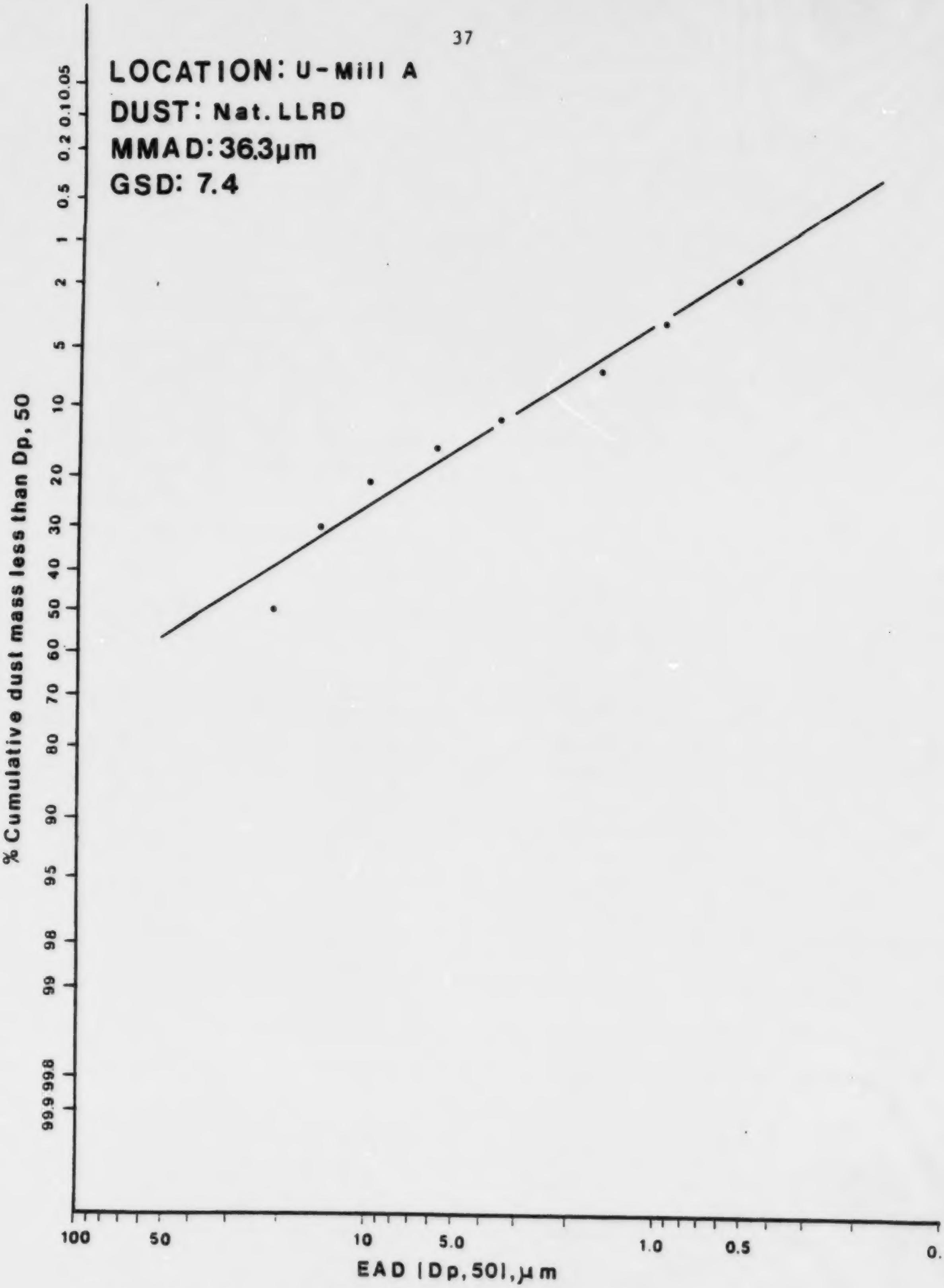


Fig. 4 - Percentage cumulative dust mass versus EAD measured with the Marple 290 at the crusher/conveyor belt transfer point.

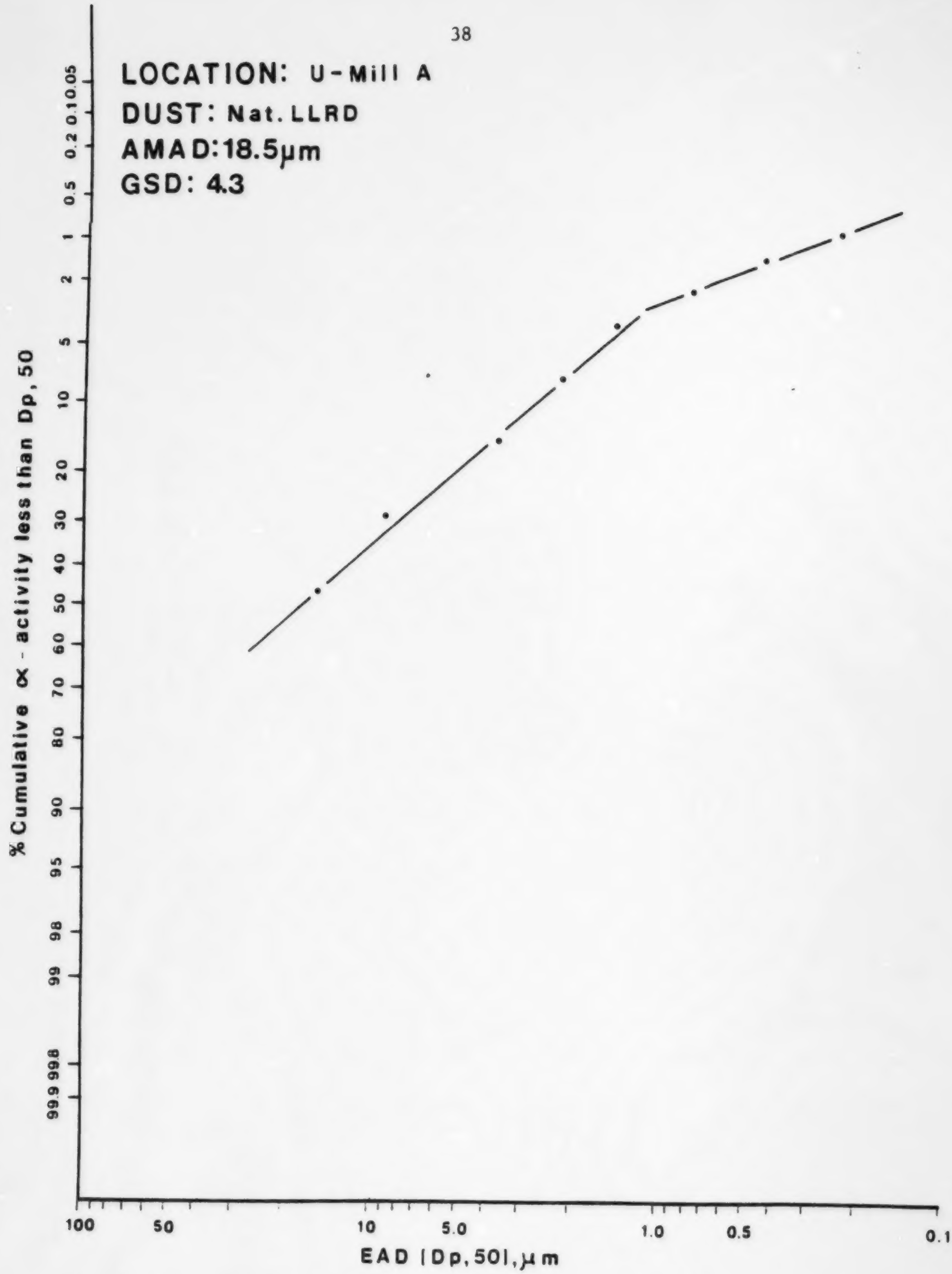


Fig. 5 - Percentage cumulative α-particle activity versus EAD measured with the Sierra 210 at the crusher/conveyor belt transfer point.

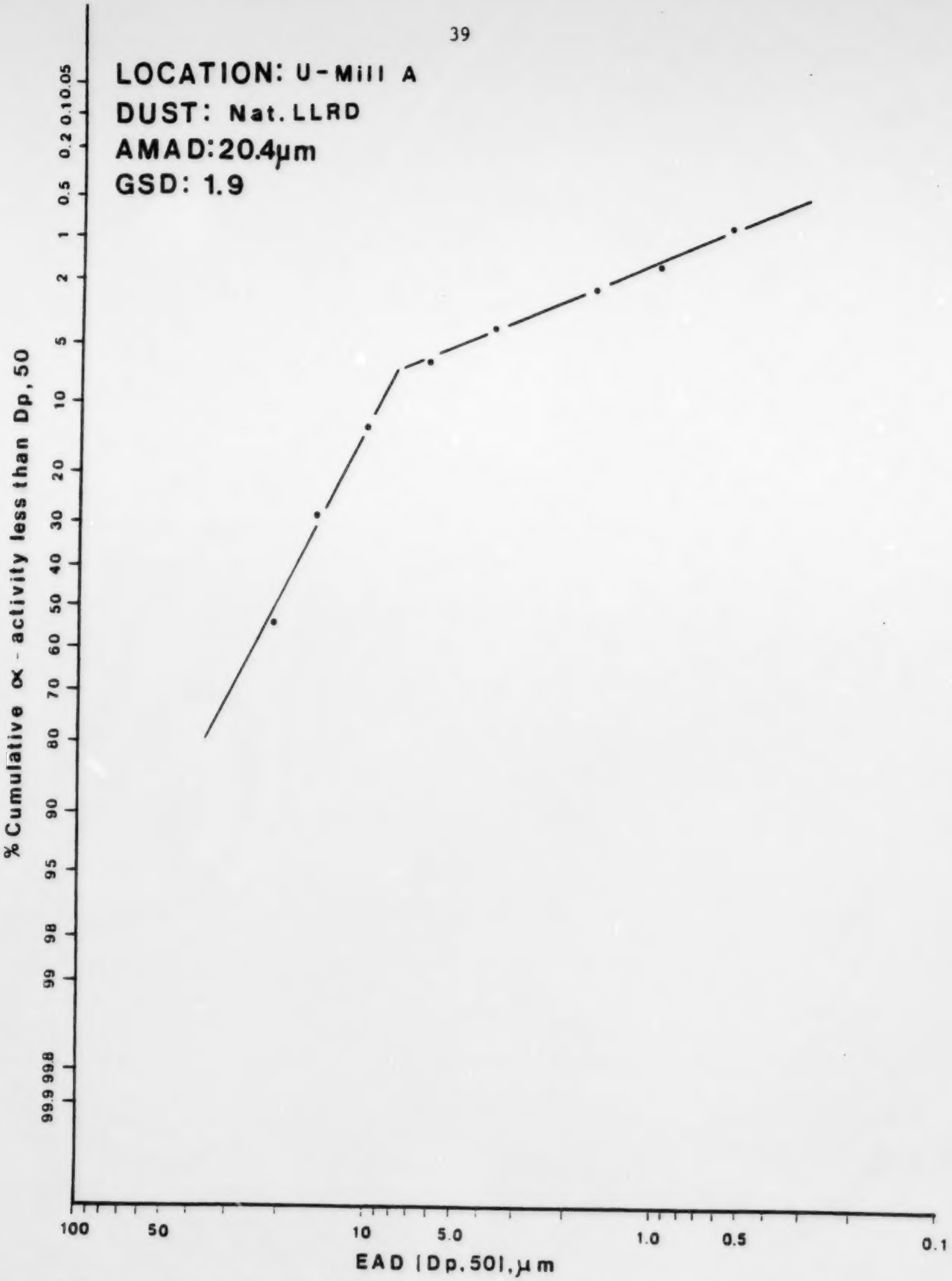


Fig. 6 - Percentage cumulative α-particle activity versus EAD measured with the Marple 290 at the crusher/conveyor belt transfer point.

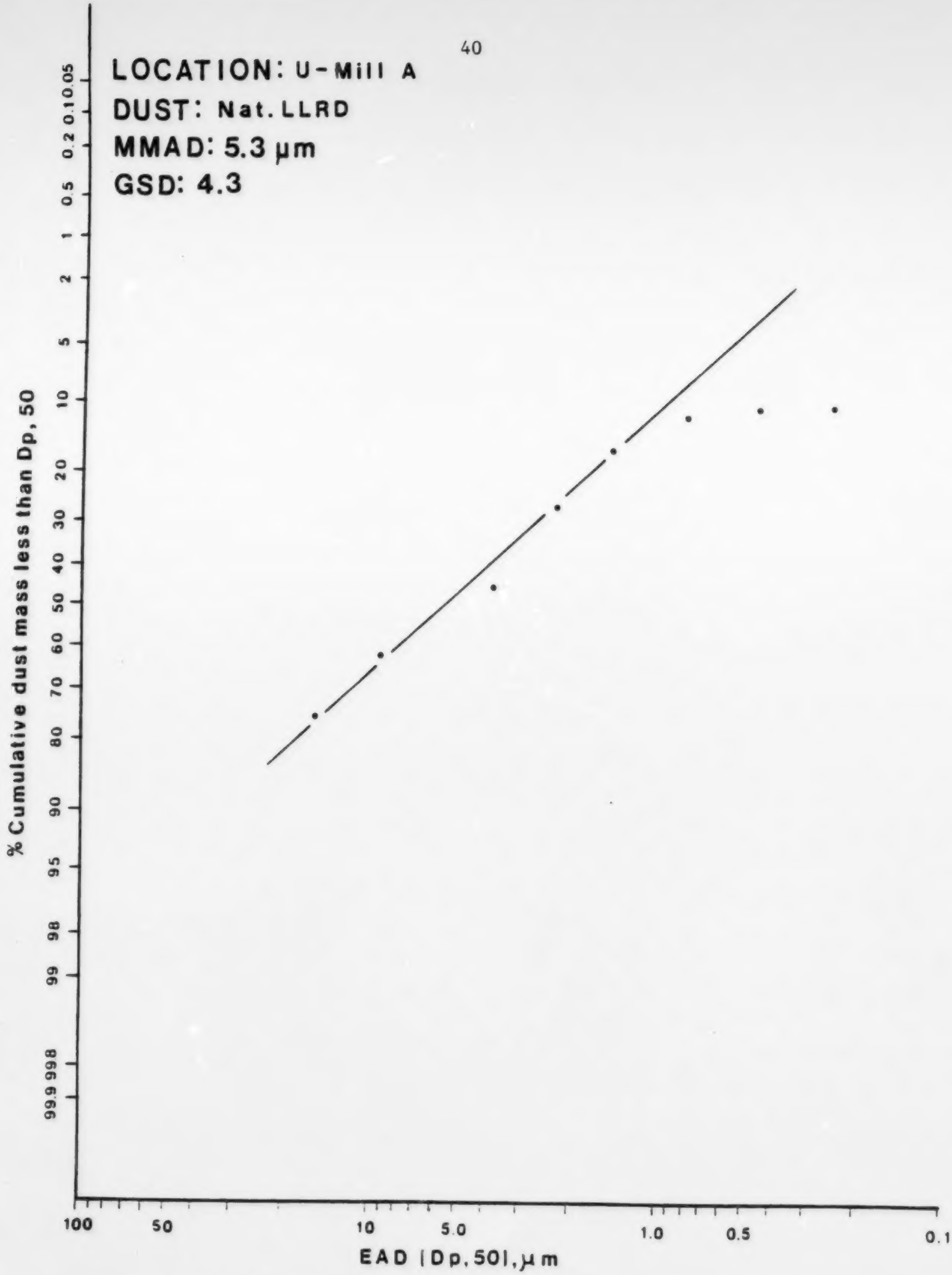


Fig. 7 - Percentage cumulative dust mass versus EAD measured with the Sierra 210 during the ball milling operation.

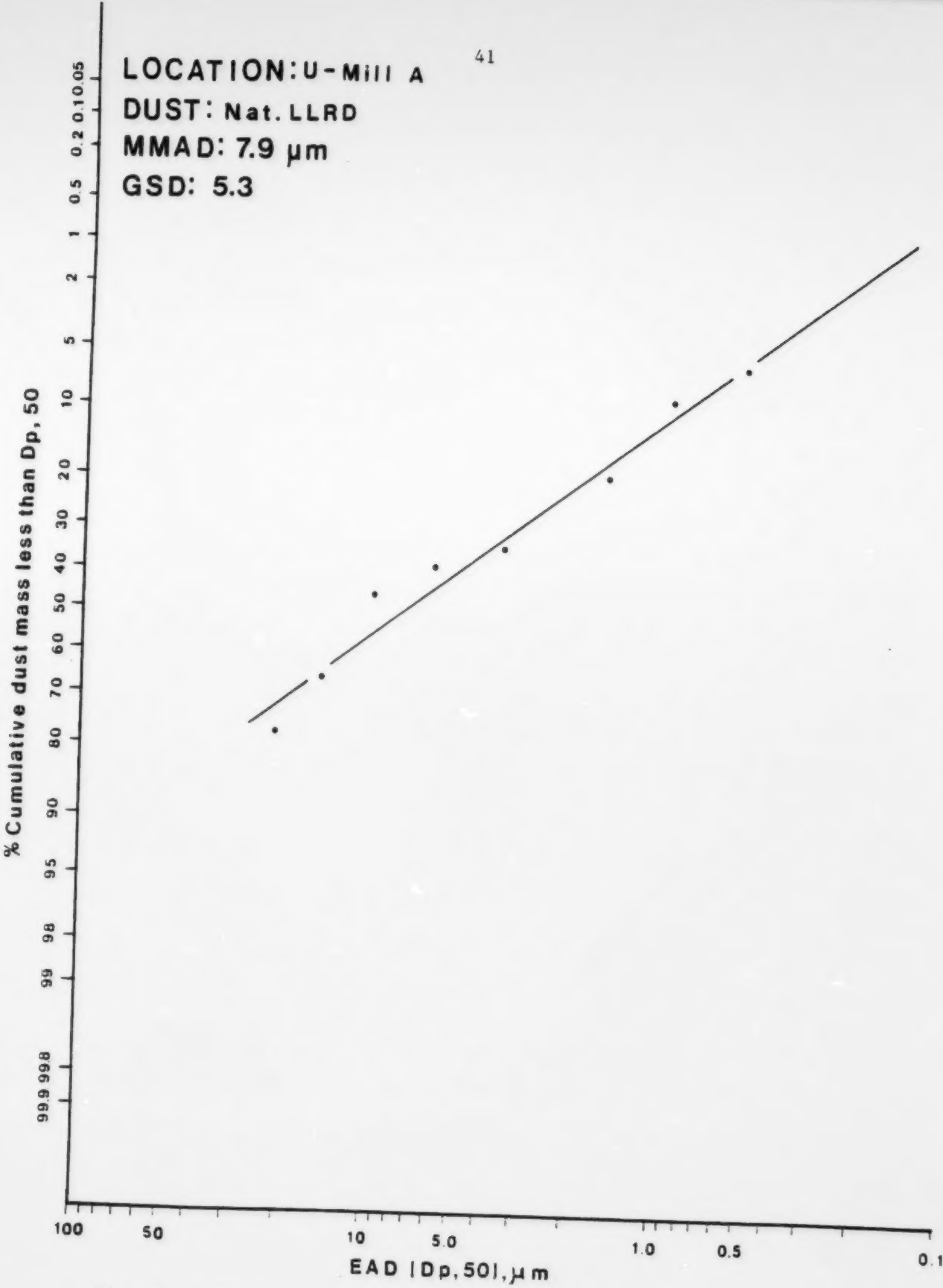


Fig. 8 - Percentage cumulative dust mass versus EAD measured with the Marple 290 during the ball milling operation.

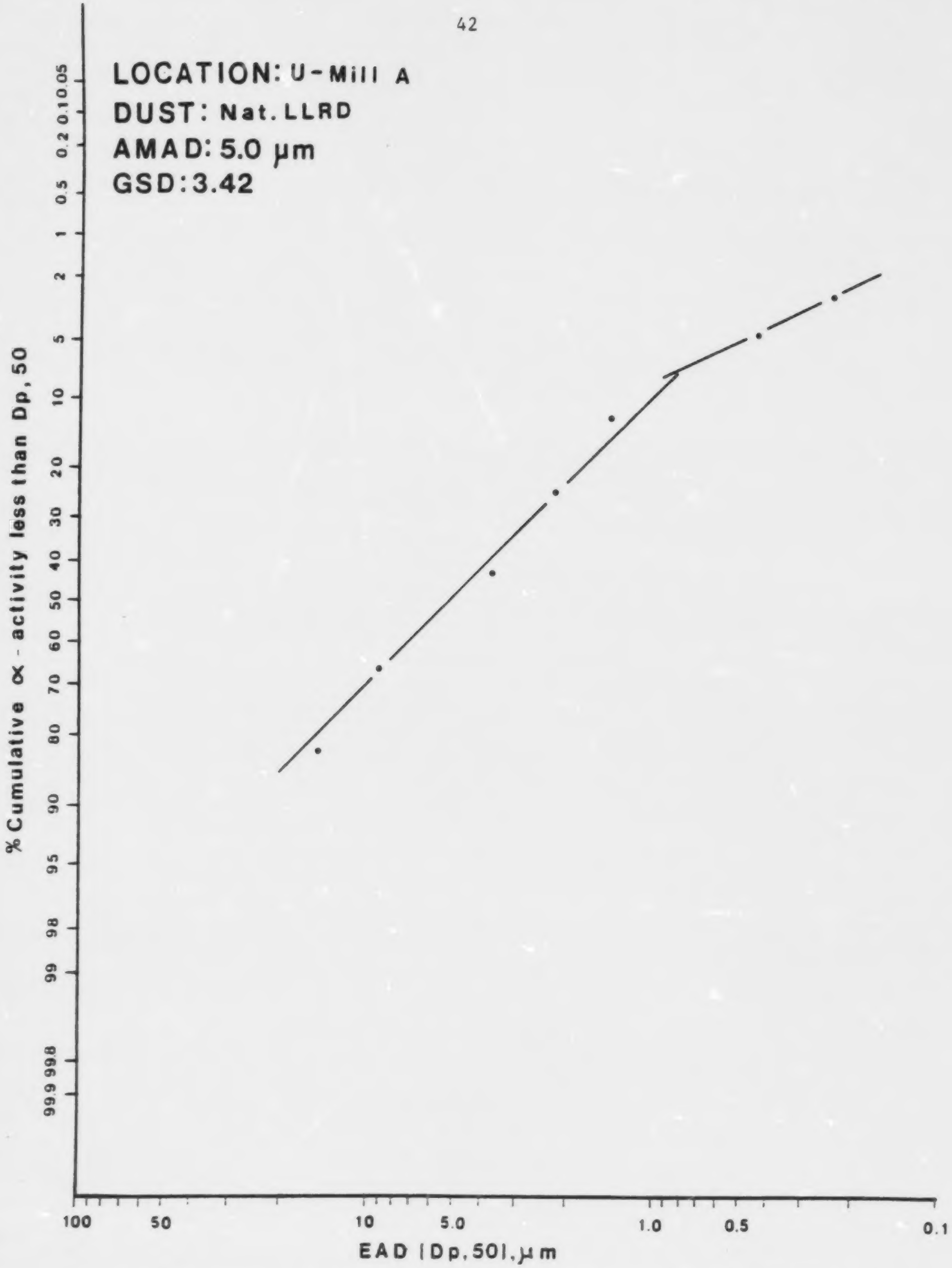


Fig. 9 - Percentage cumulative α-particle activity versus EAD measured with the Sierra 210 during the ball milling operation.

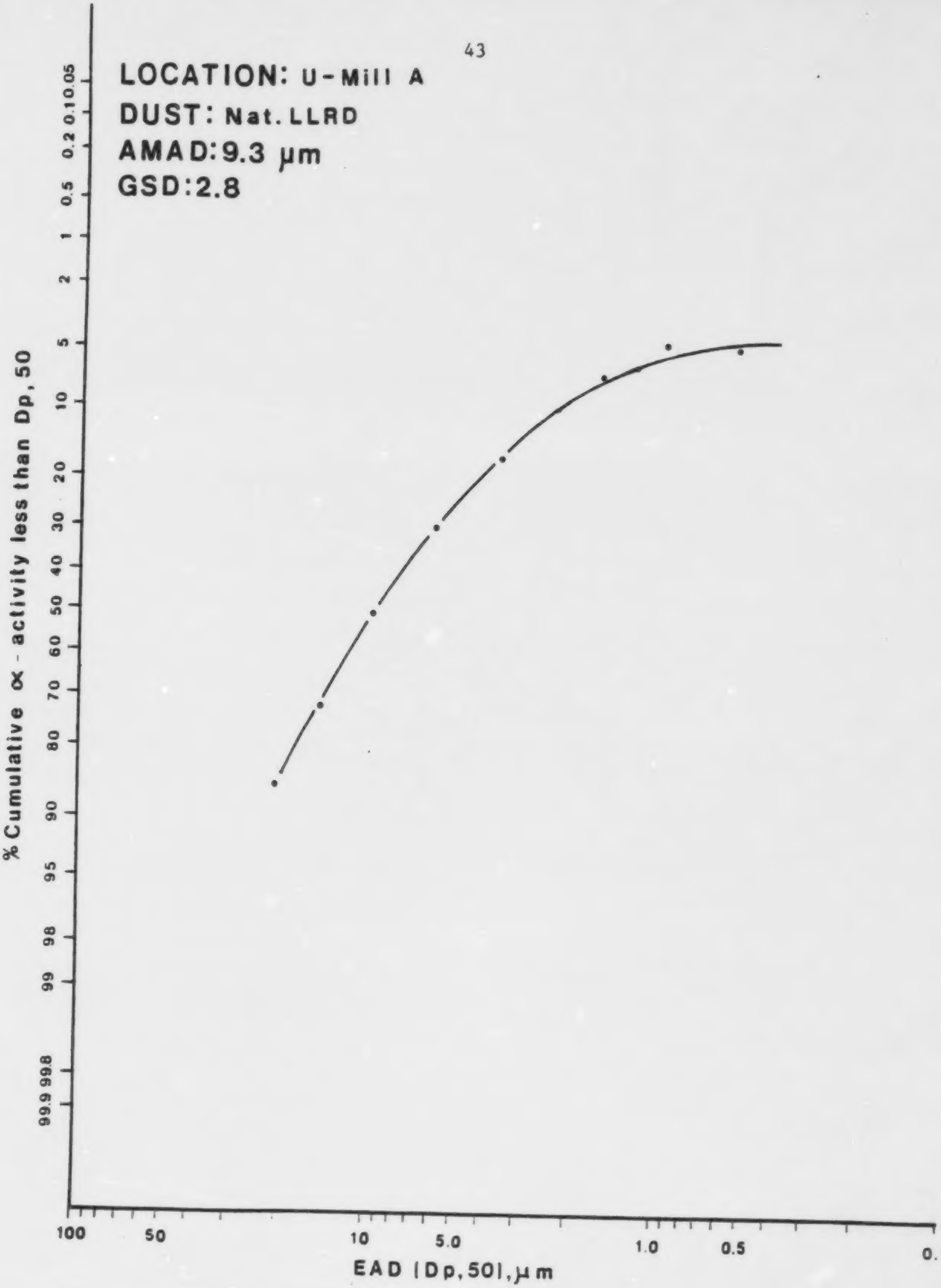


Fig. 10 - Percentage cumulative α-particle activity versus EAD measured with the Marple 290 during the ball milling operation.

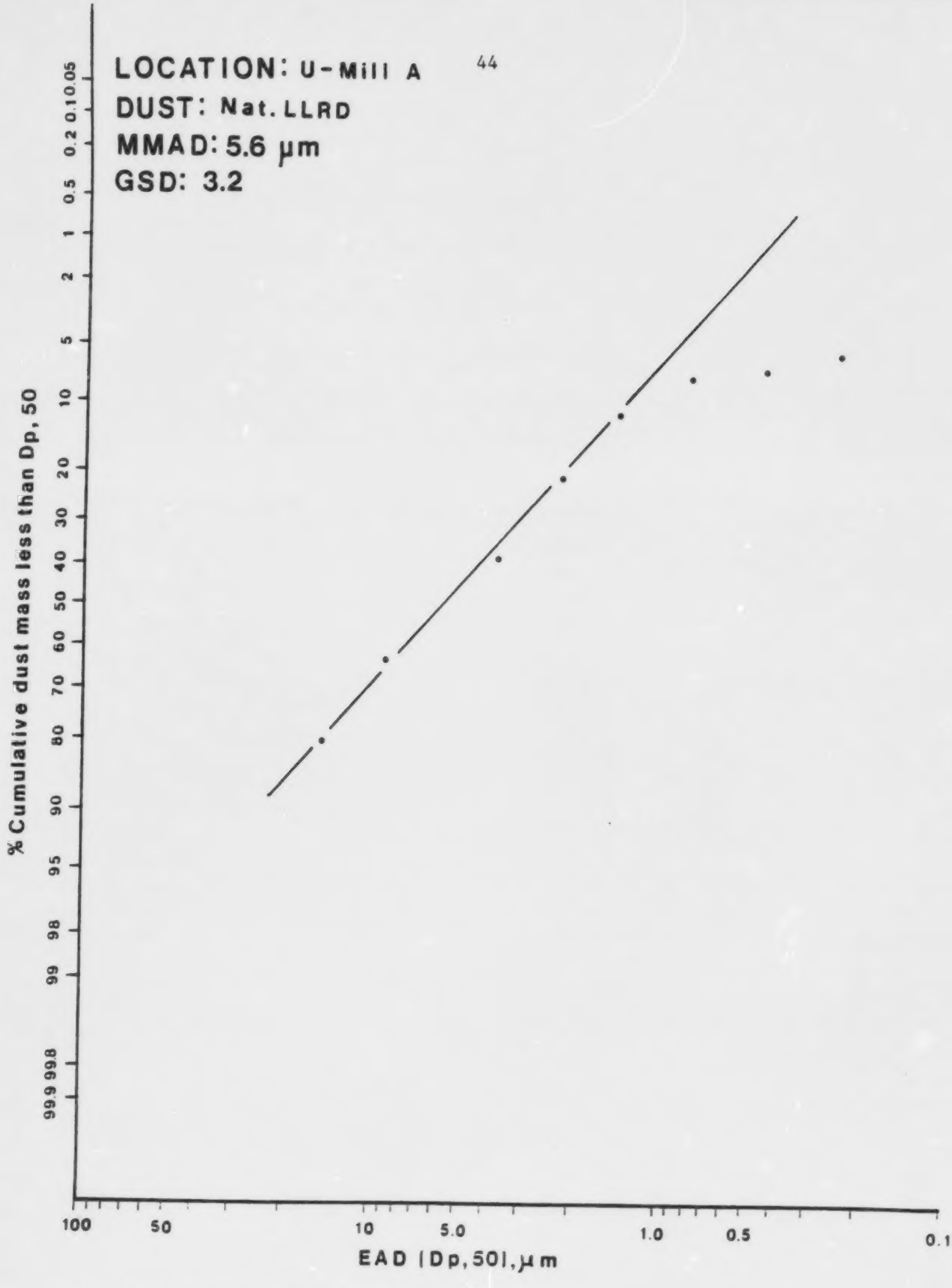


Fig. 11 - Percentage cumulative dust mass versus EAD measured with the Sierra 210 during the yellowcake precipitation operation.

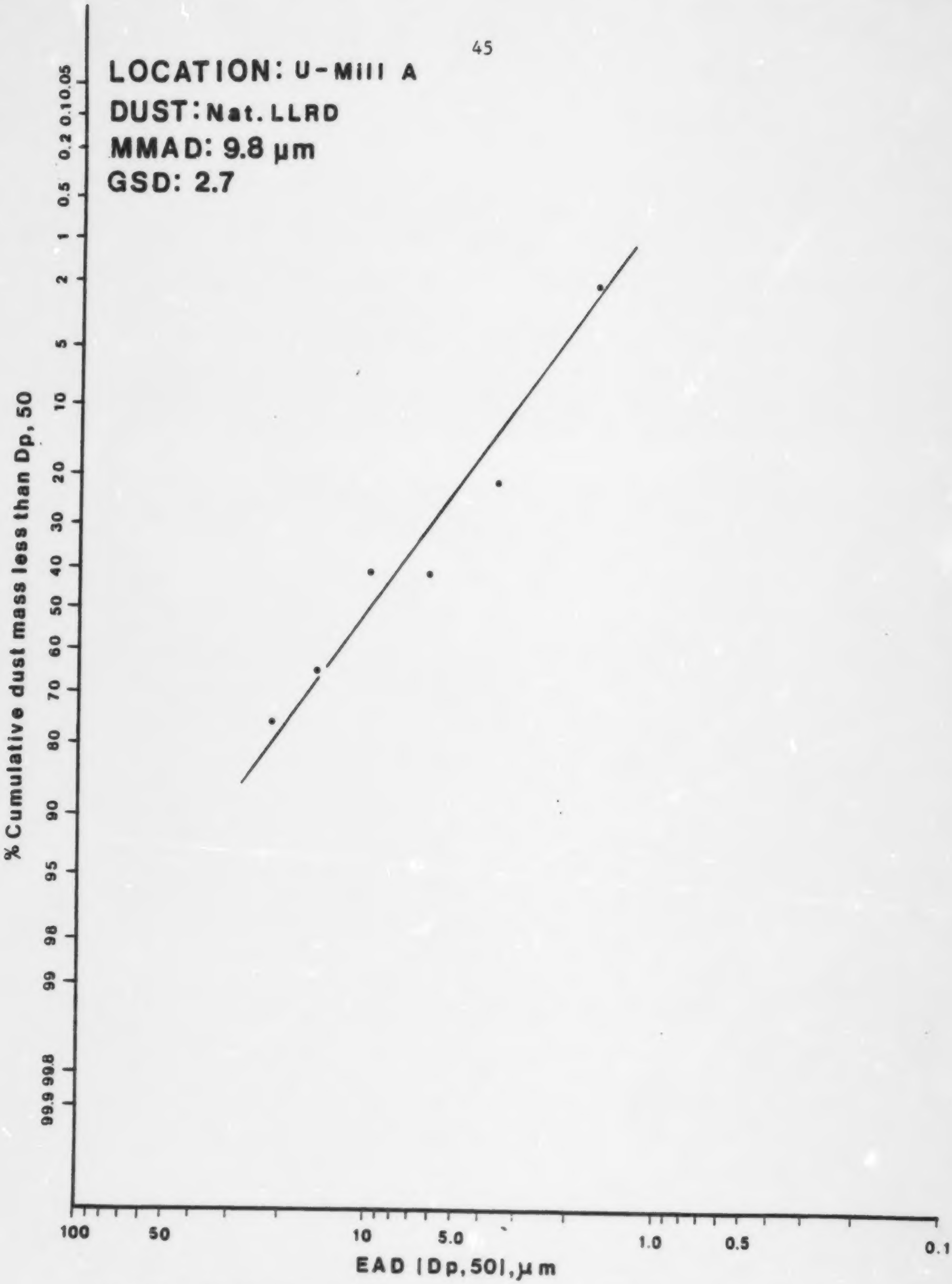


Fig. 12 - Percentage cumulative dust mass versus EAD measured with the Marple 290 during the yellowcake precipitation operation.

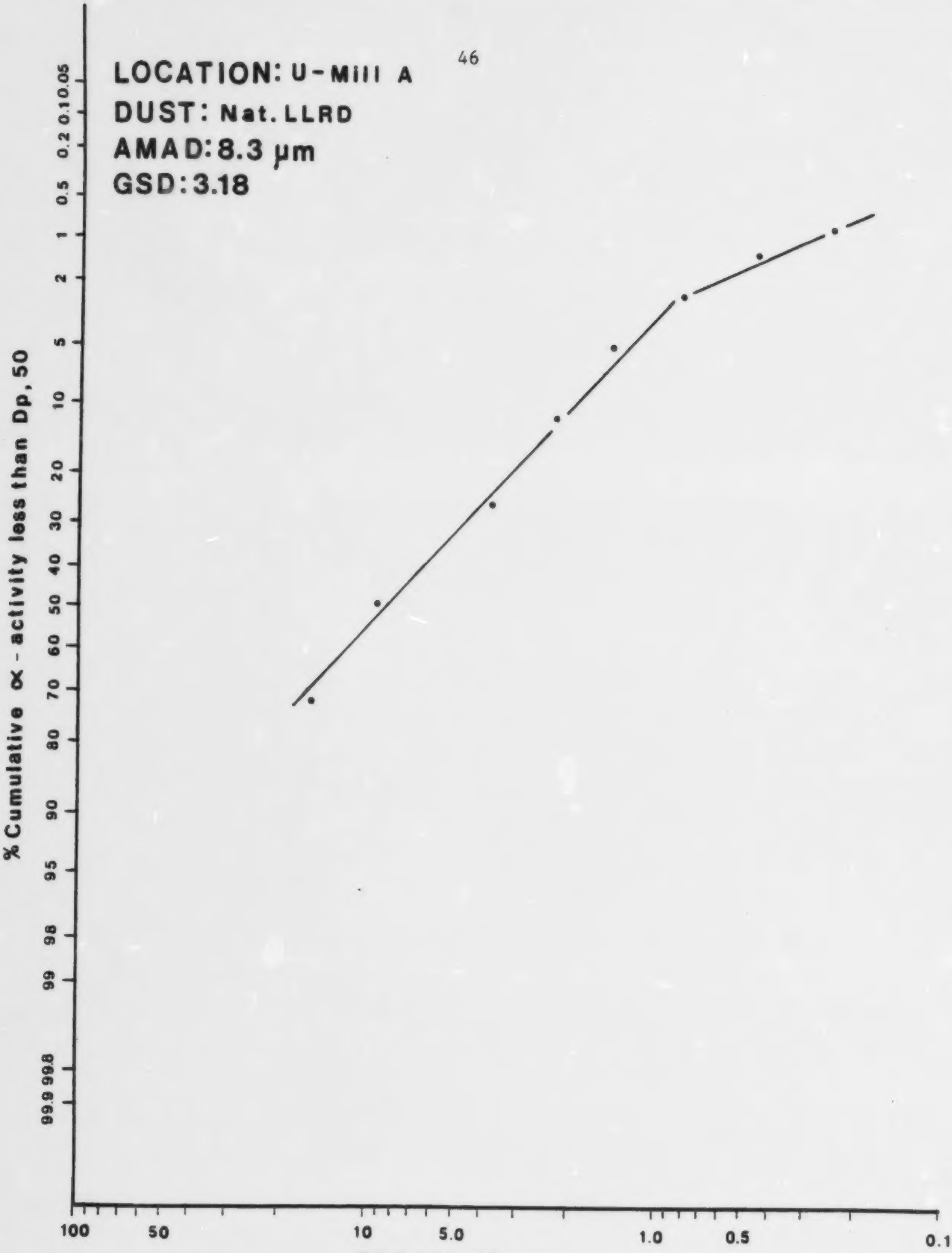


Fig. 13 - Percentage cumulative α-particle activity versus EAD measured with the Sierra 210 during the yellowcake precipitation operation.

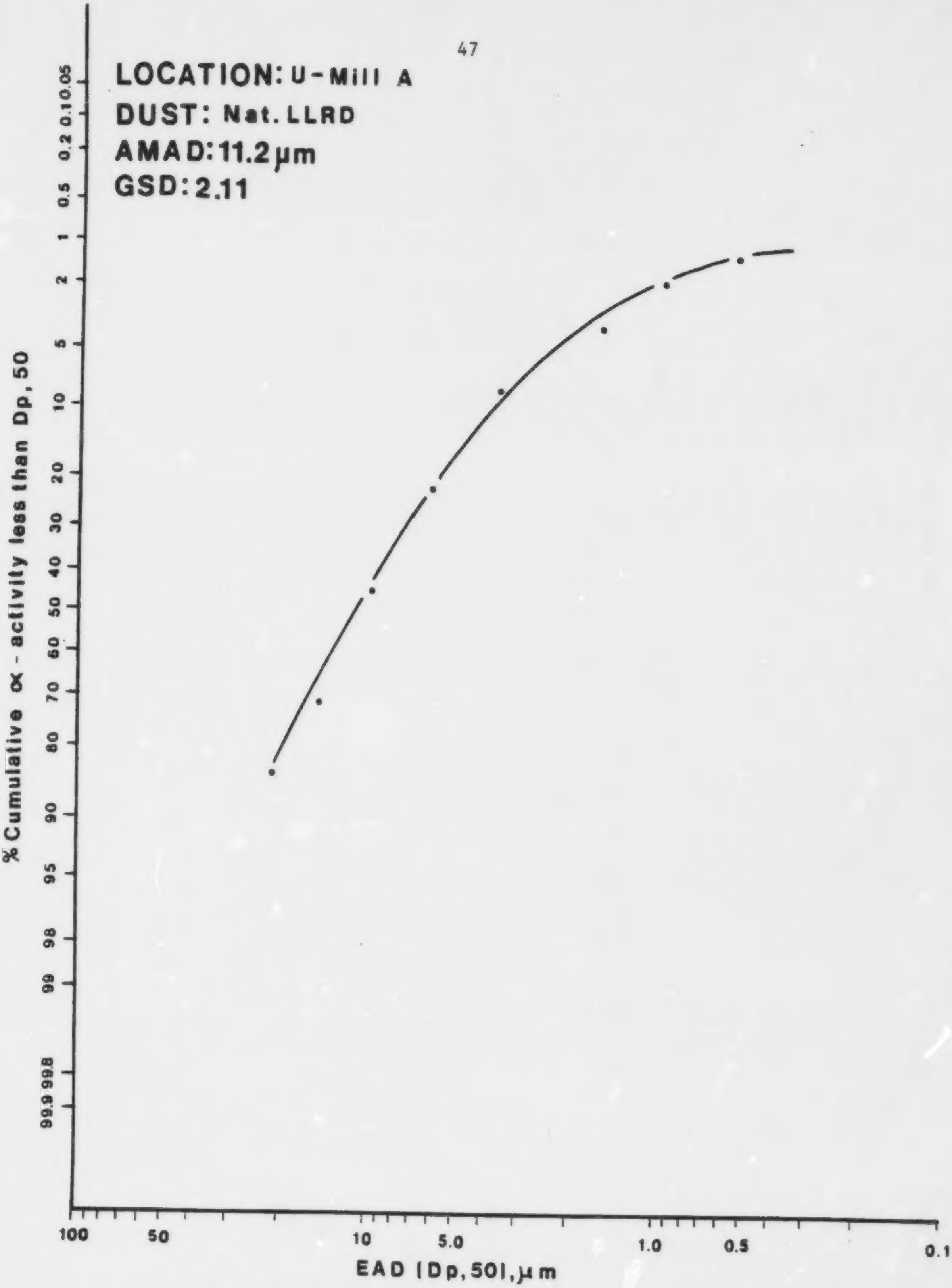


Fig. 14 - Percentage cumulative α-particle activity versus EAD measured with the Marple 290 during the yellowcake precipitation operation.

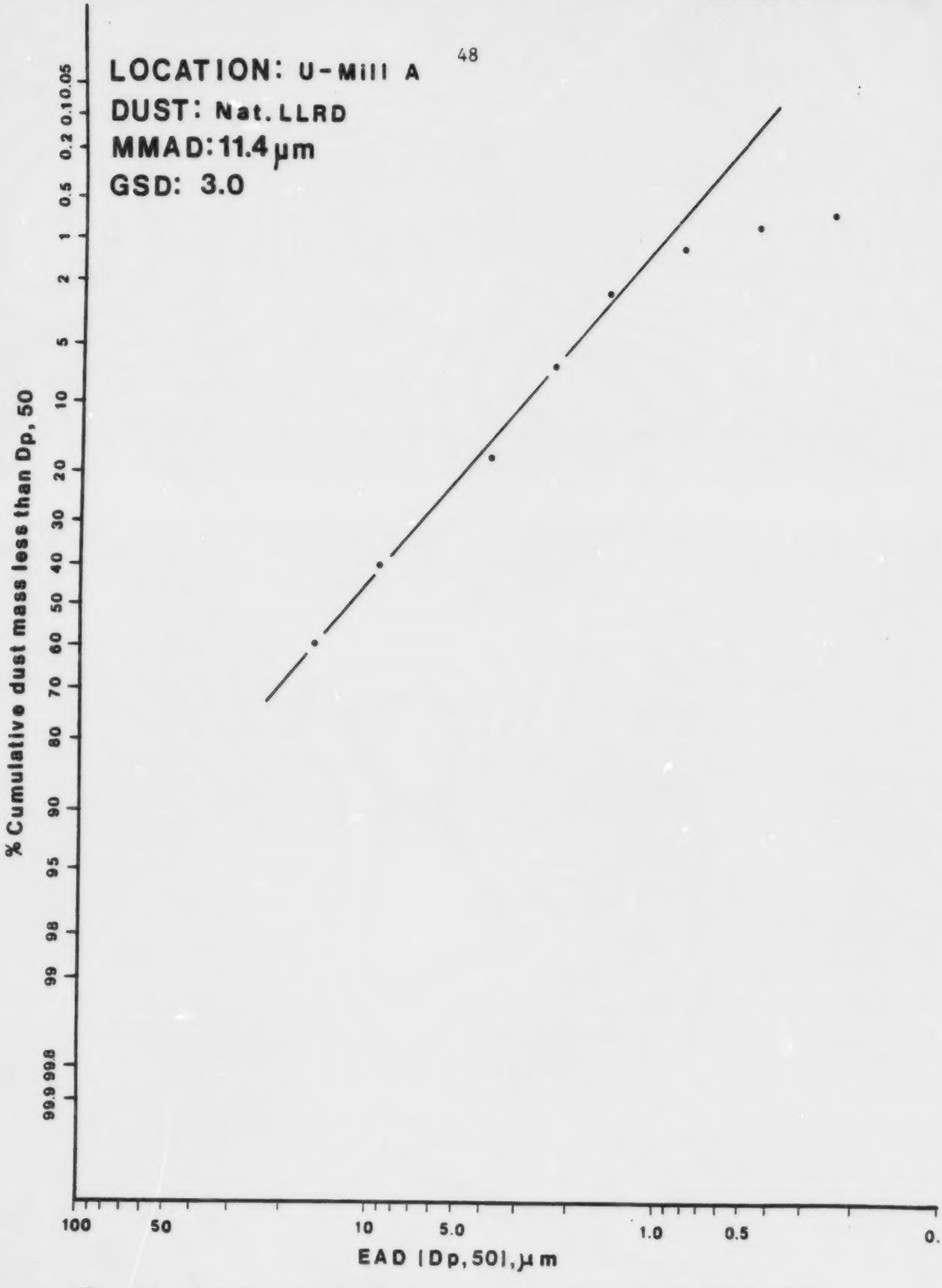


Fig. 15 - Percentage cumulative dust mass versus EAD measured with the Sierra 210 during the cone crushing operation.

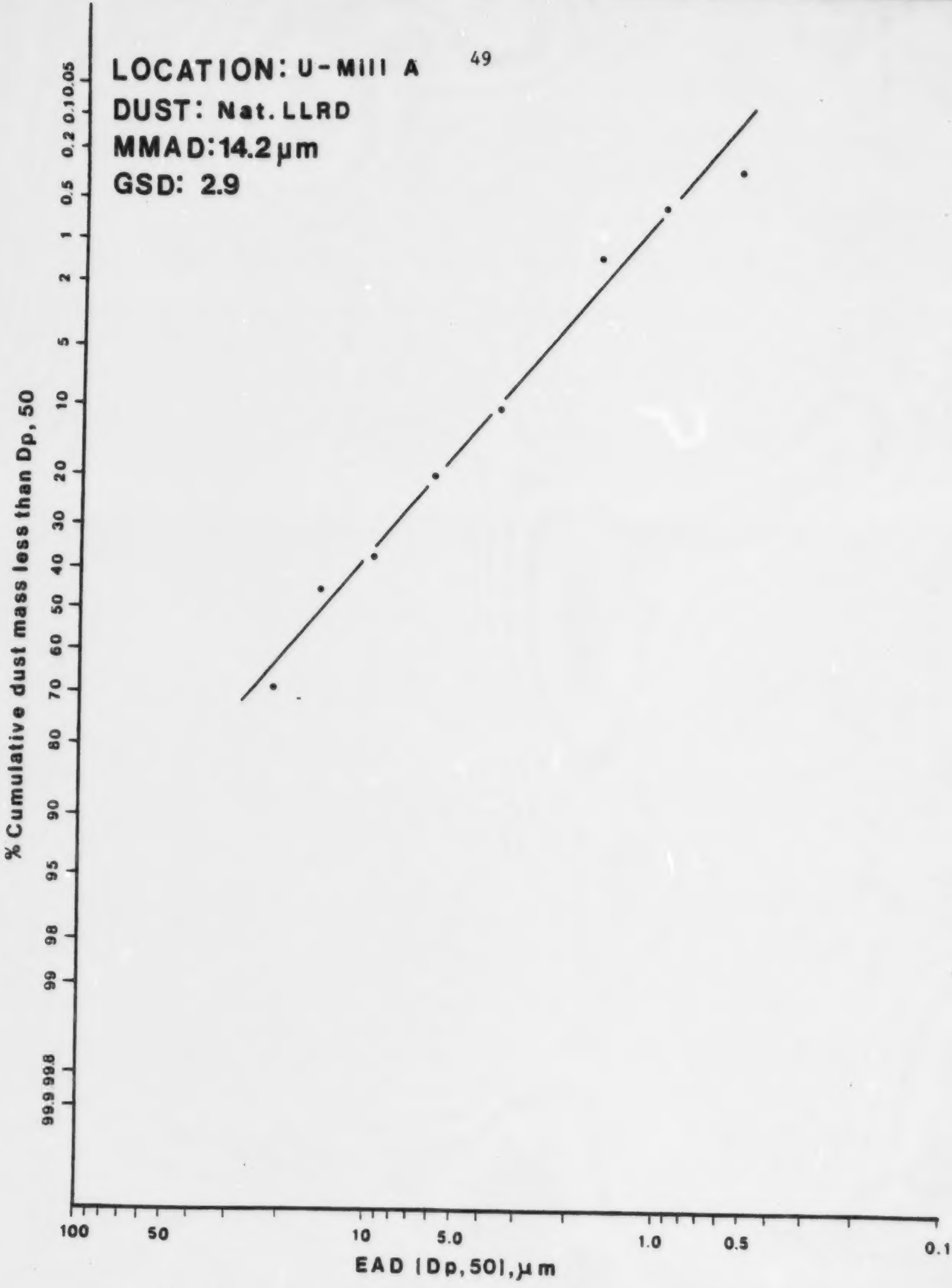


Fig. 16 - Percentage cumulative dust mass versus EAD measured with the Marple 290 during the cone crushing operation.

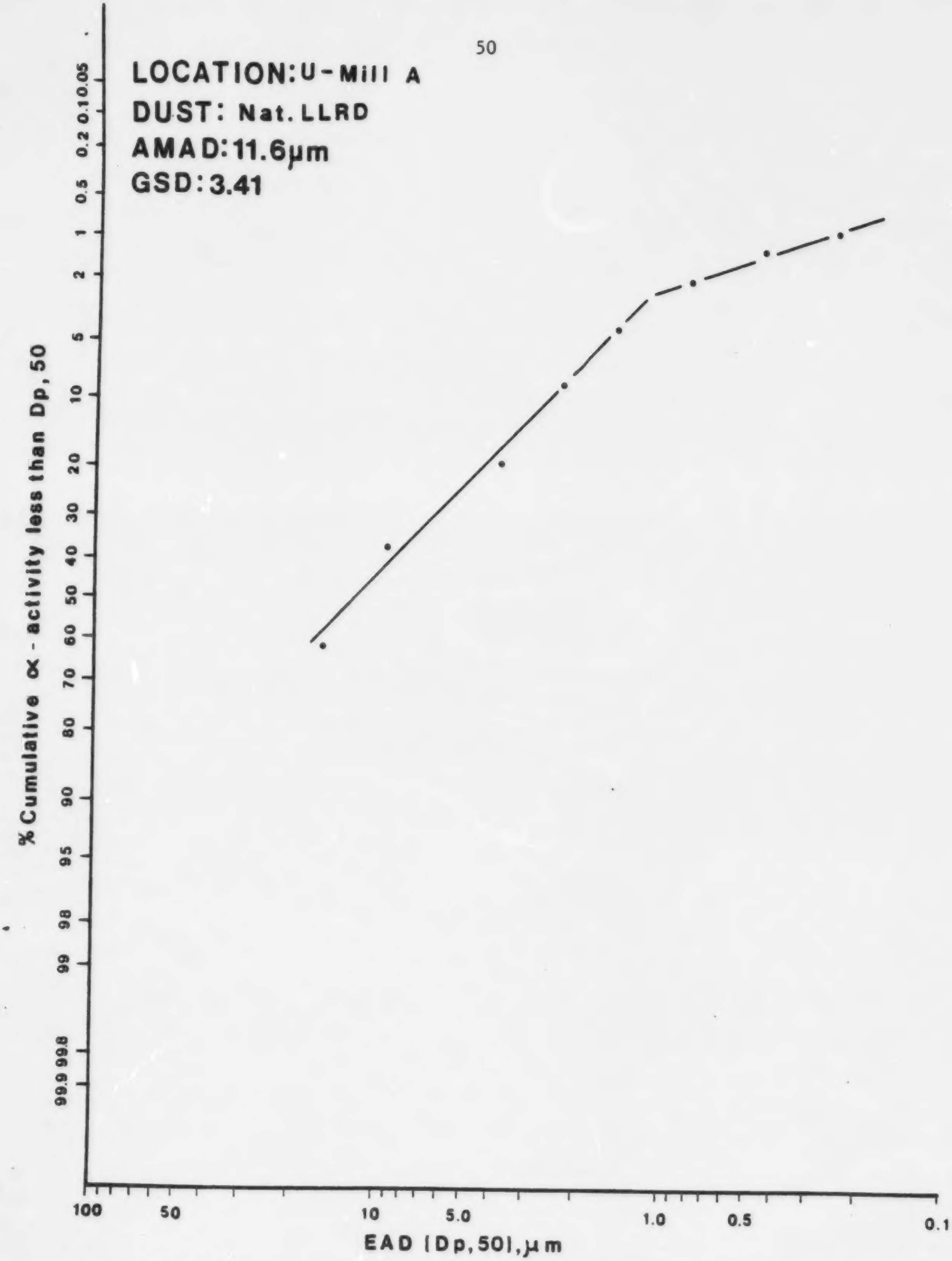


Fig. 17 - Percentage cumulative α-particle activity versus EAD measured with the Sierra 210 during the cone crushing operation.

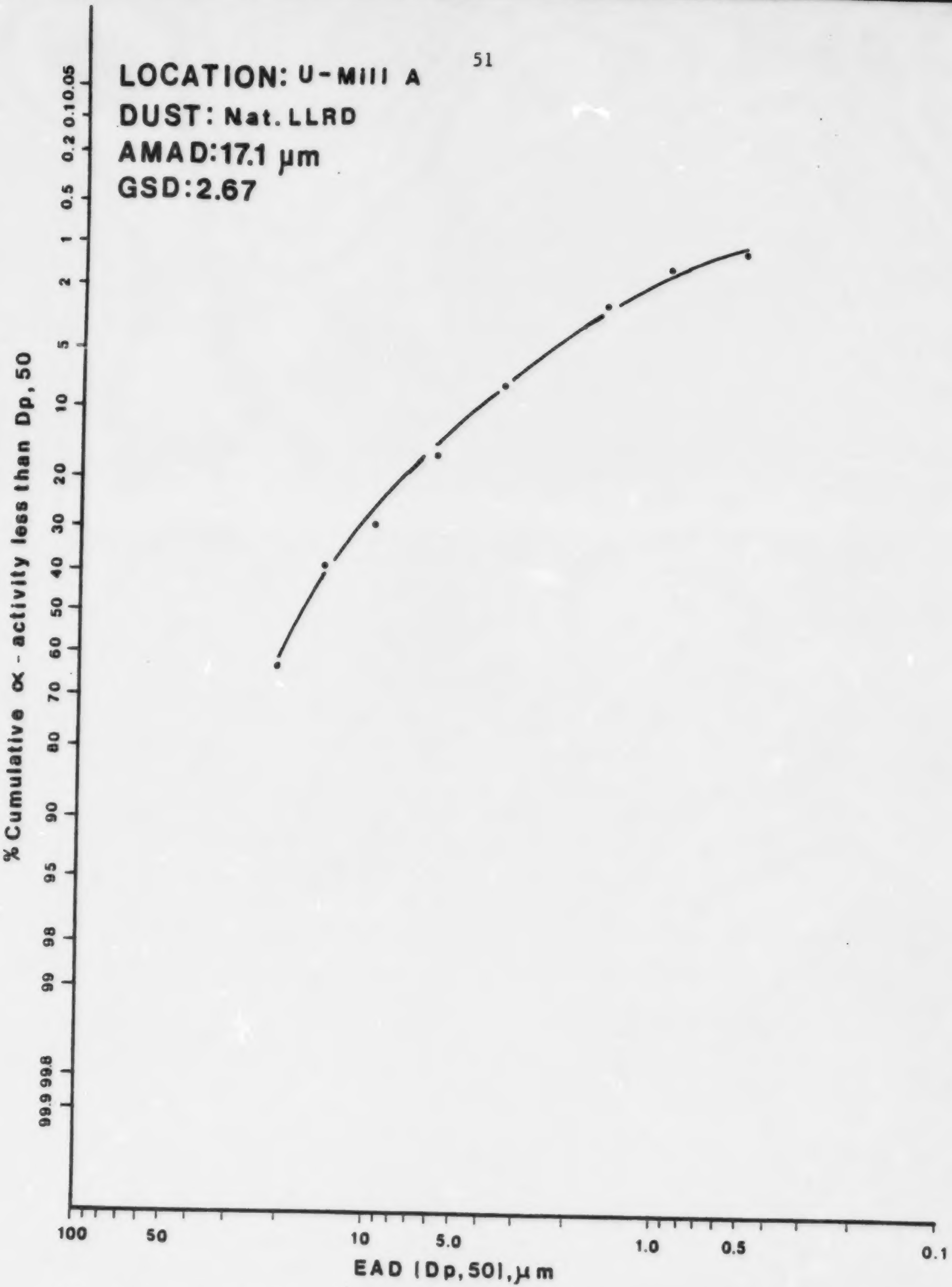


Fig. 18 - Percentage cumulative α-particle activity versus EAD measured with the Marple 290 during the cone crushing operation.

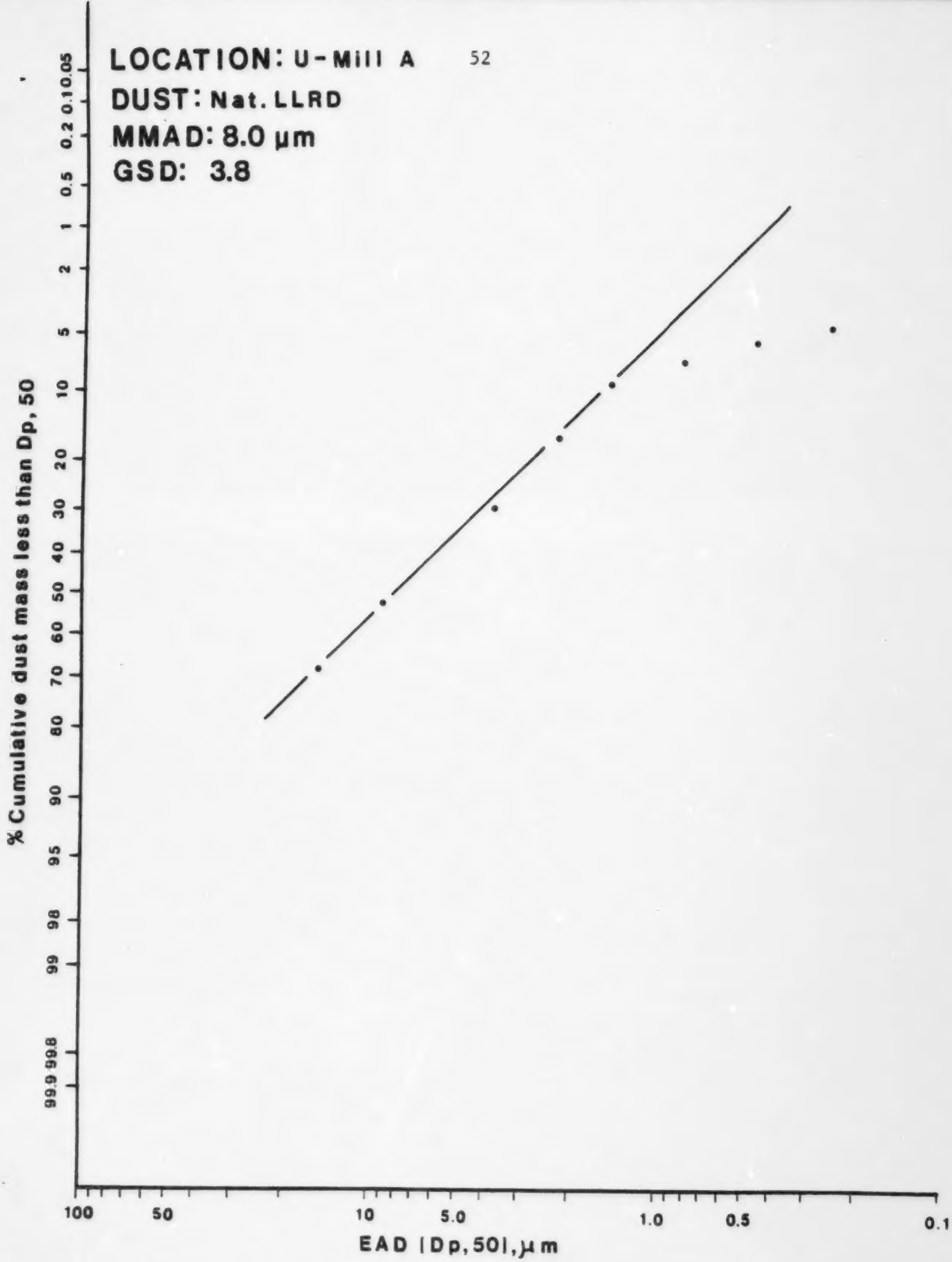


Fig. 19 - Percentage cumulative dust mass versus EAD measured with the Sierra 210 at the hopper/conveyor belt/ball mill area.

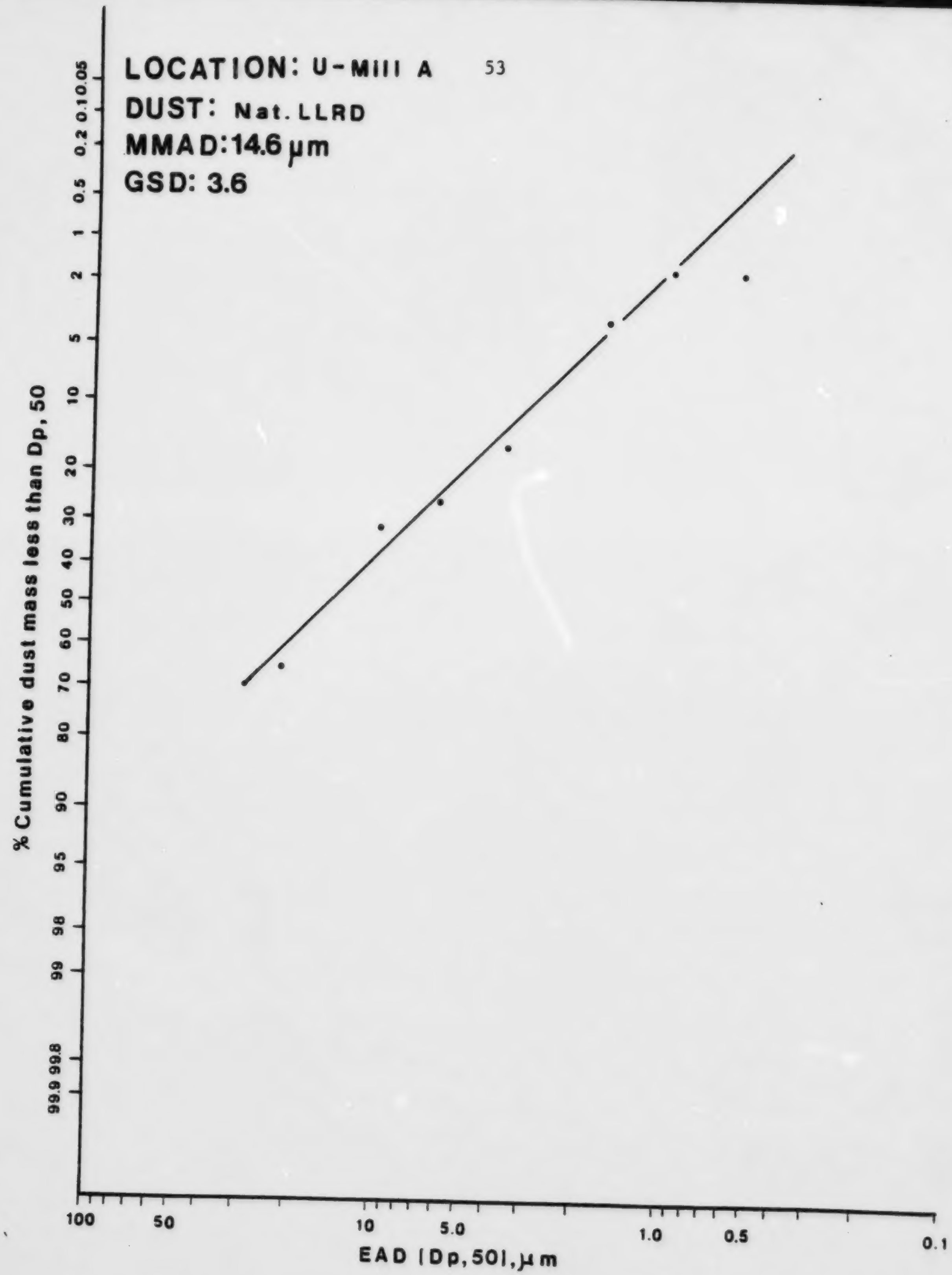


Fig. 20 - Percentage cumulative dust mass versus EAD measured with the Marple 290 at the hopper/conveyor belt/ball mill area.

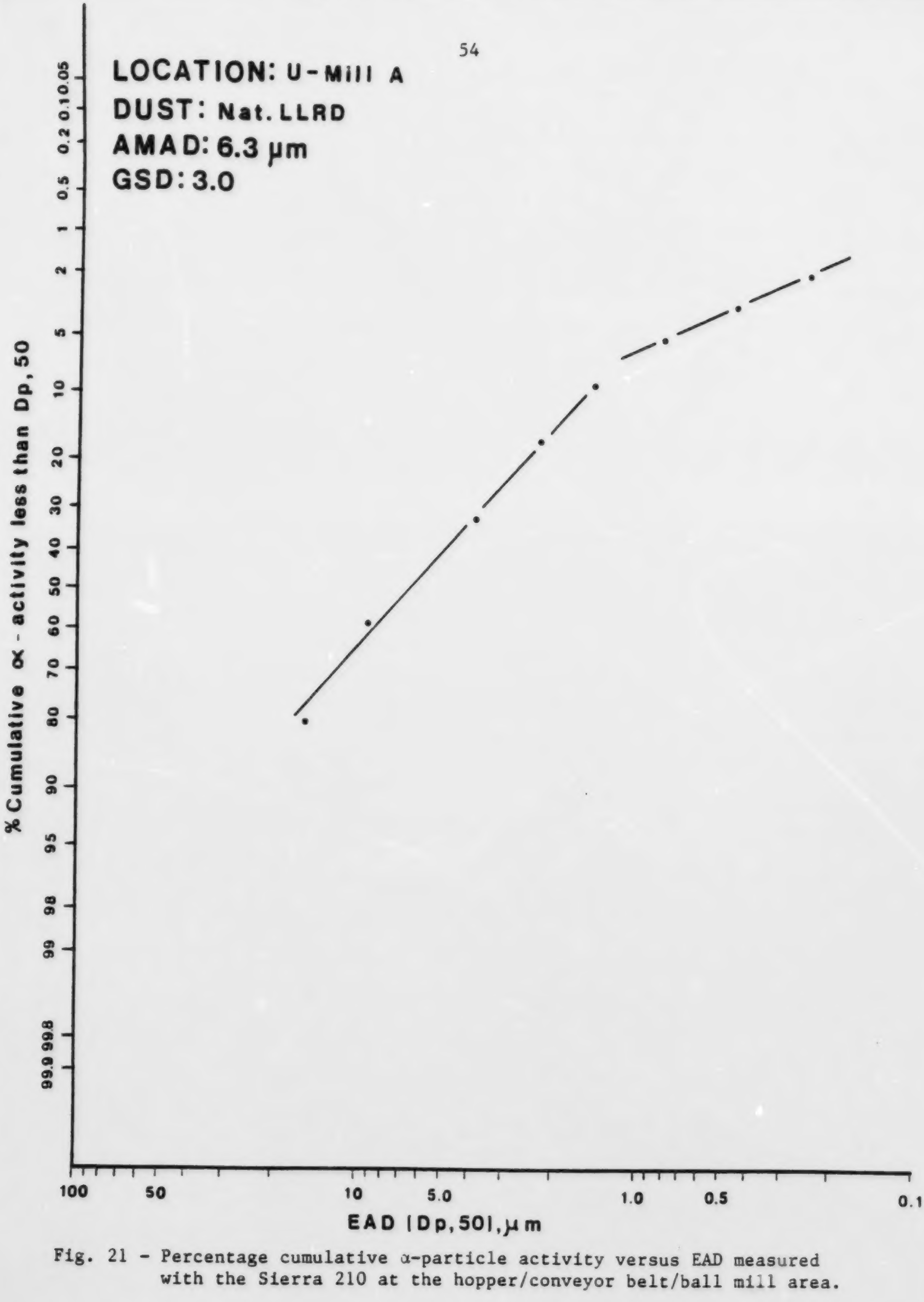


Fig. 21 - Percentage cumulative α-particle activity versus EAD measured with the Sierra 210 at the hopper/conveyor belt/ball mill area.

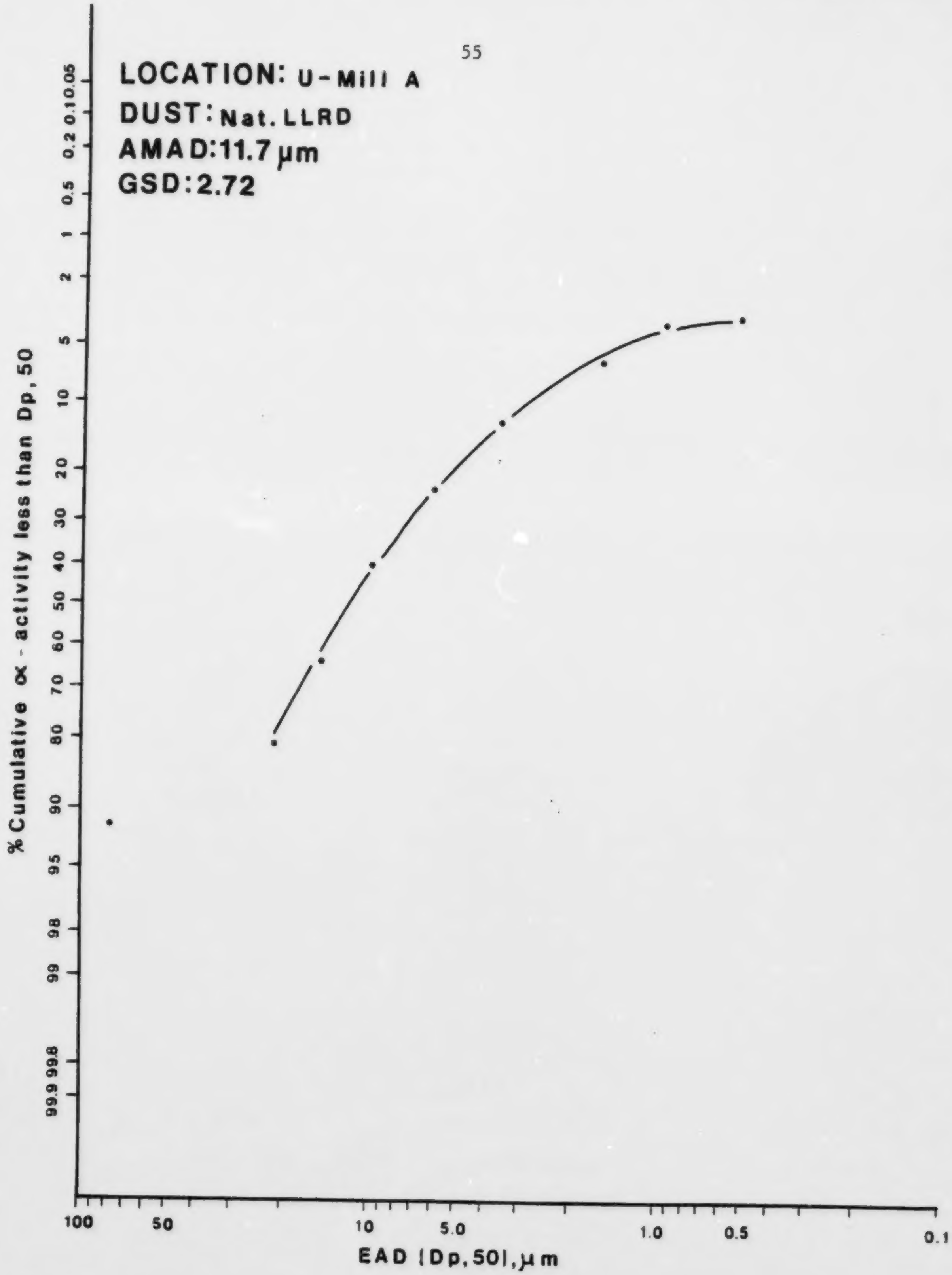


Fig. 22 - Percentage cumulative α-particle activity versus EAD measured with the Marple 290 at the hopper/conveyor belt/ball mill area.

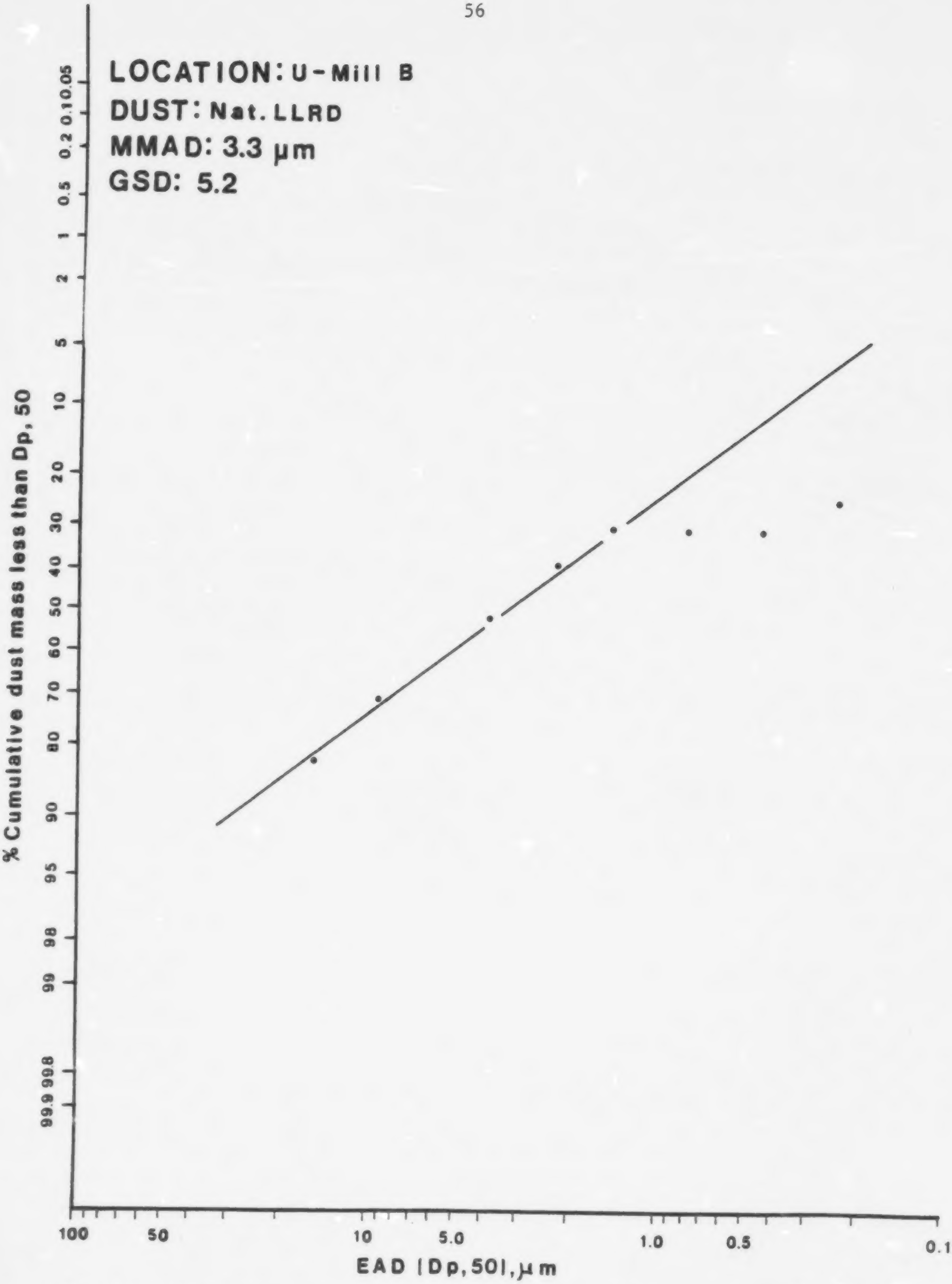


Fig. 23 - Percentage cumulative dust mass versus EAD measured with the Sierra 210 during the S.A.G. milling operation.

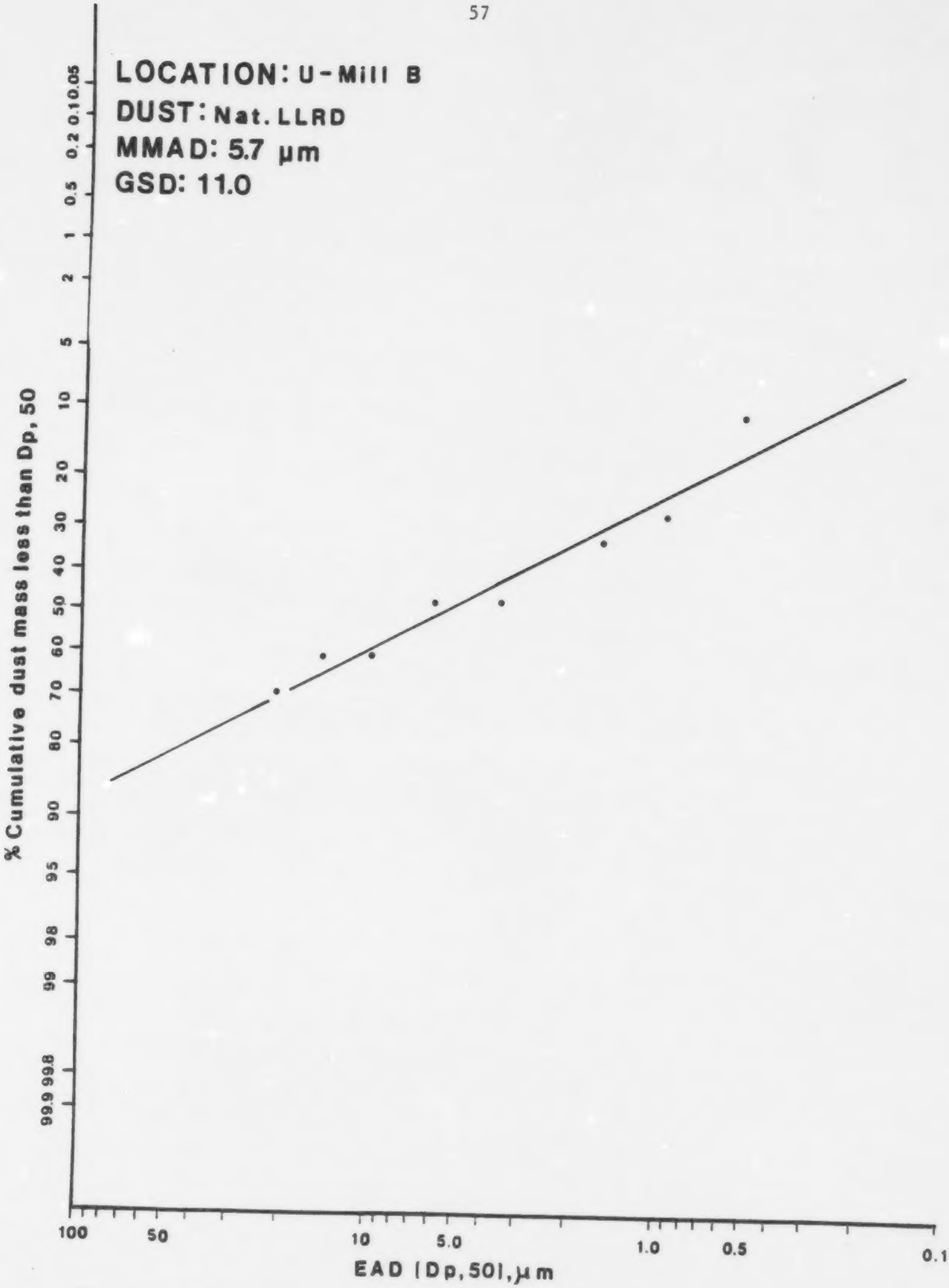


Fig. 24 - Percentage cumulative dust mass versus EAD measured with the Marple 290 during the S.A.G. milling operation.

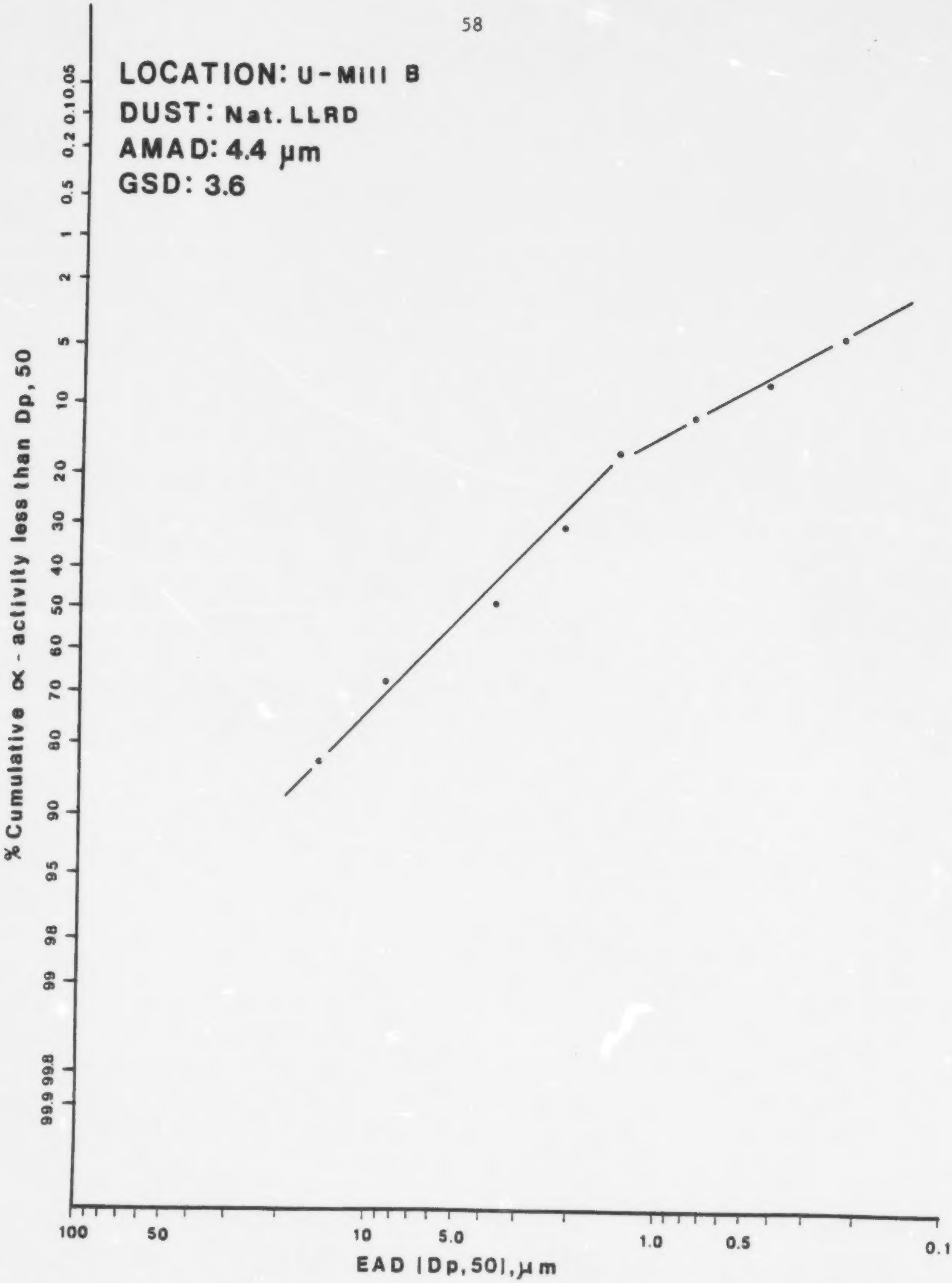


Fig. 25 - Percentage cumulative α-particle activity versus EAD measured with the Sierra 210 during the S.A.G. milling operation.

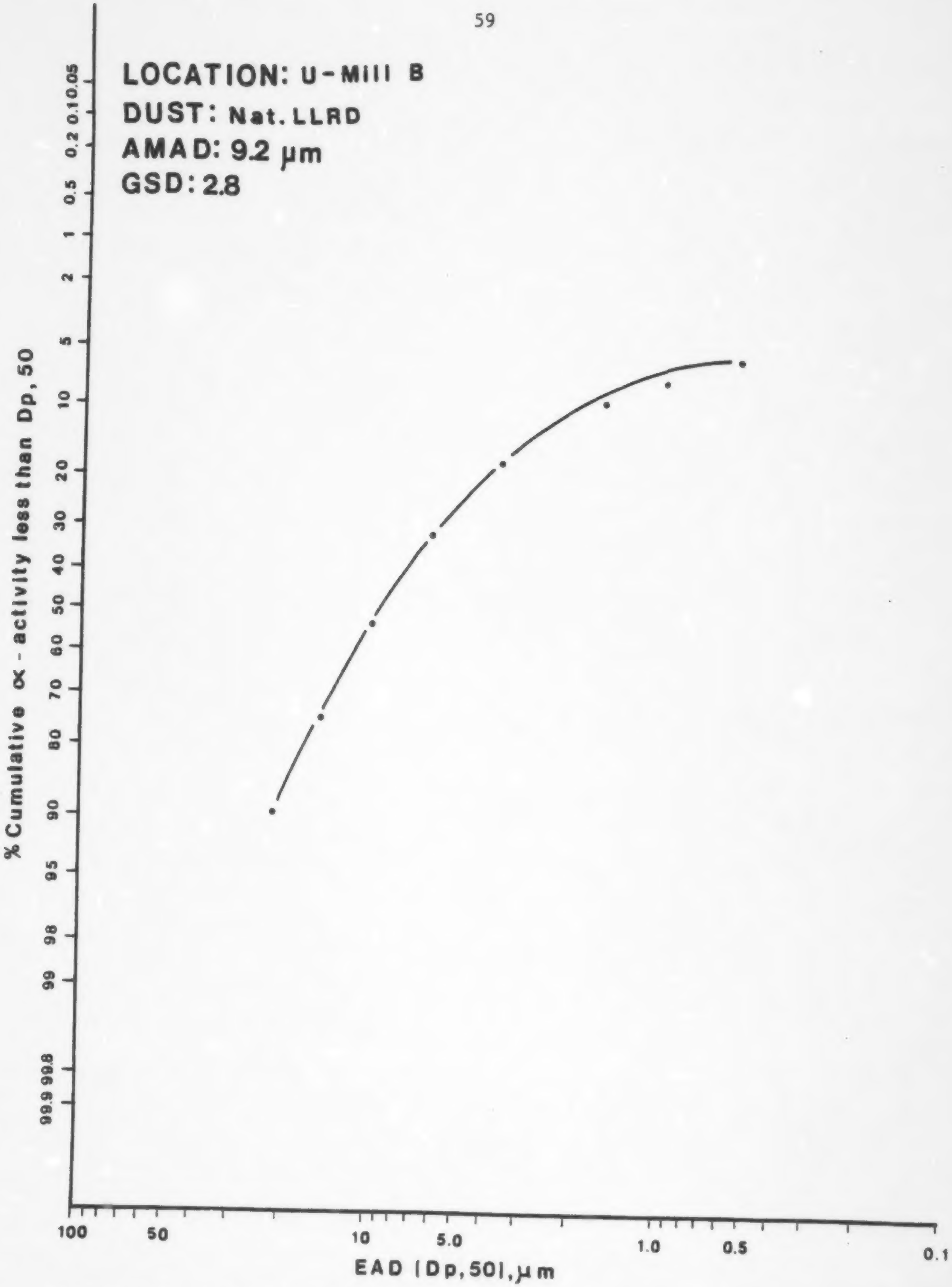


FIg. 26 - Percentage cumulative α-particle activity versus EAD measured with the Marple 290 during the S.A.G. milling operation.

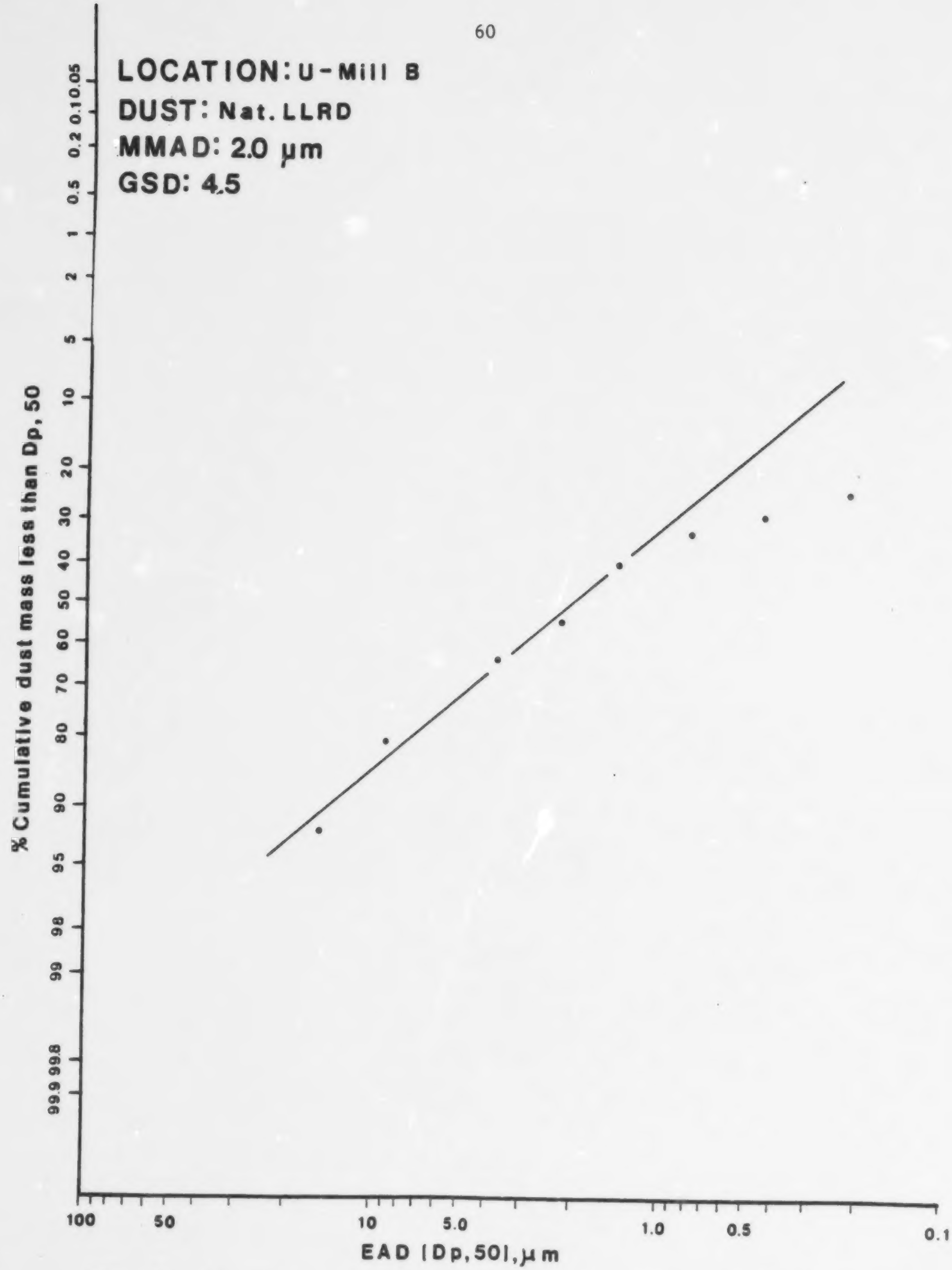


Fig. 27 - Percentage cumulative dust mass versus EAD measured with the Sierra 210 during the lime slaking operation.

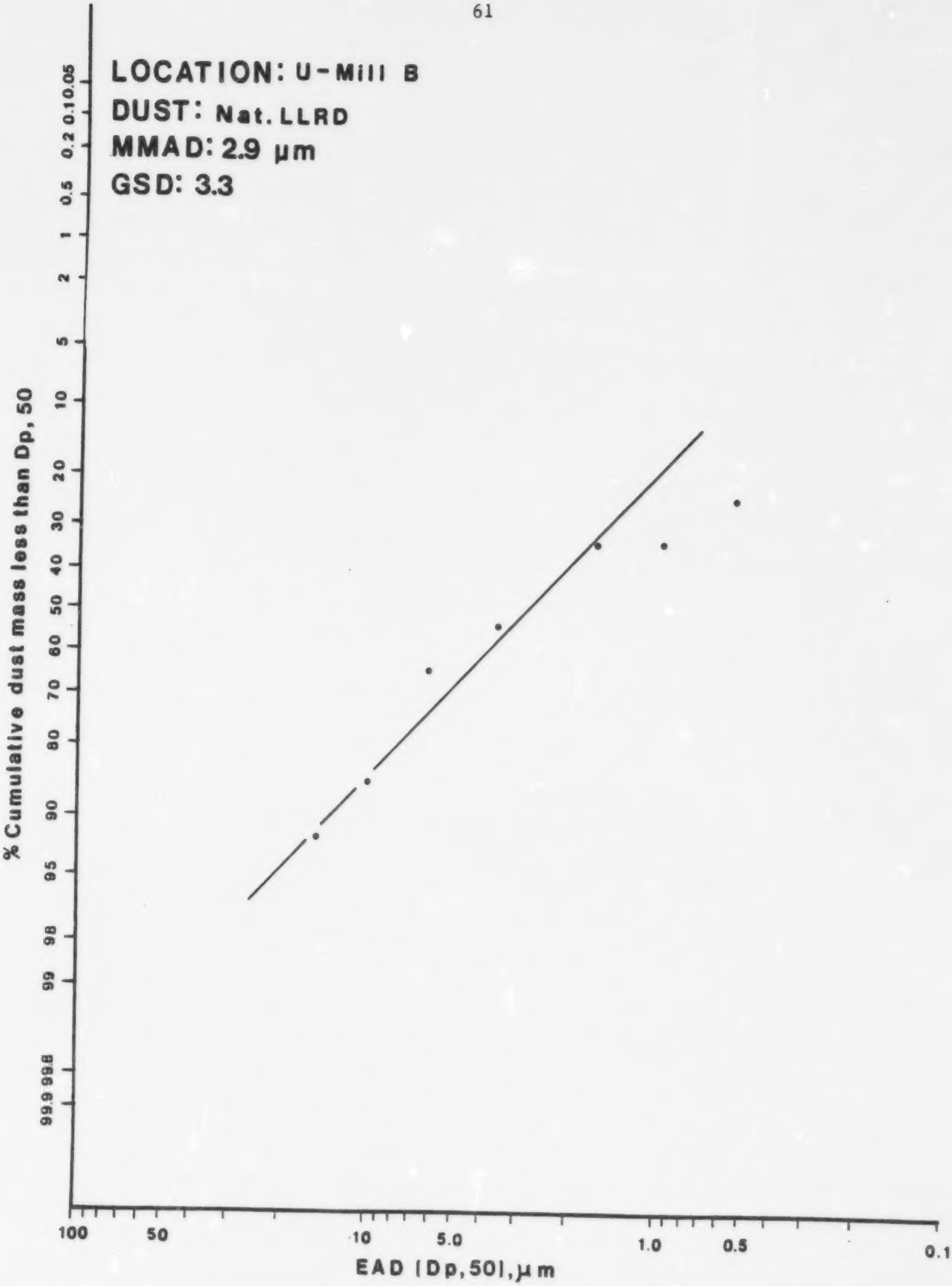


Fig. 28 - Percentage cumulative dust mass versus EAD measured with the Marple 290 during the lime slaking operation.

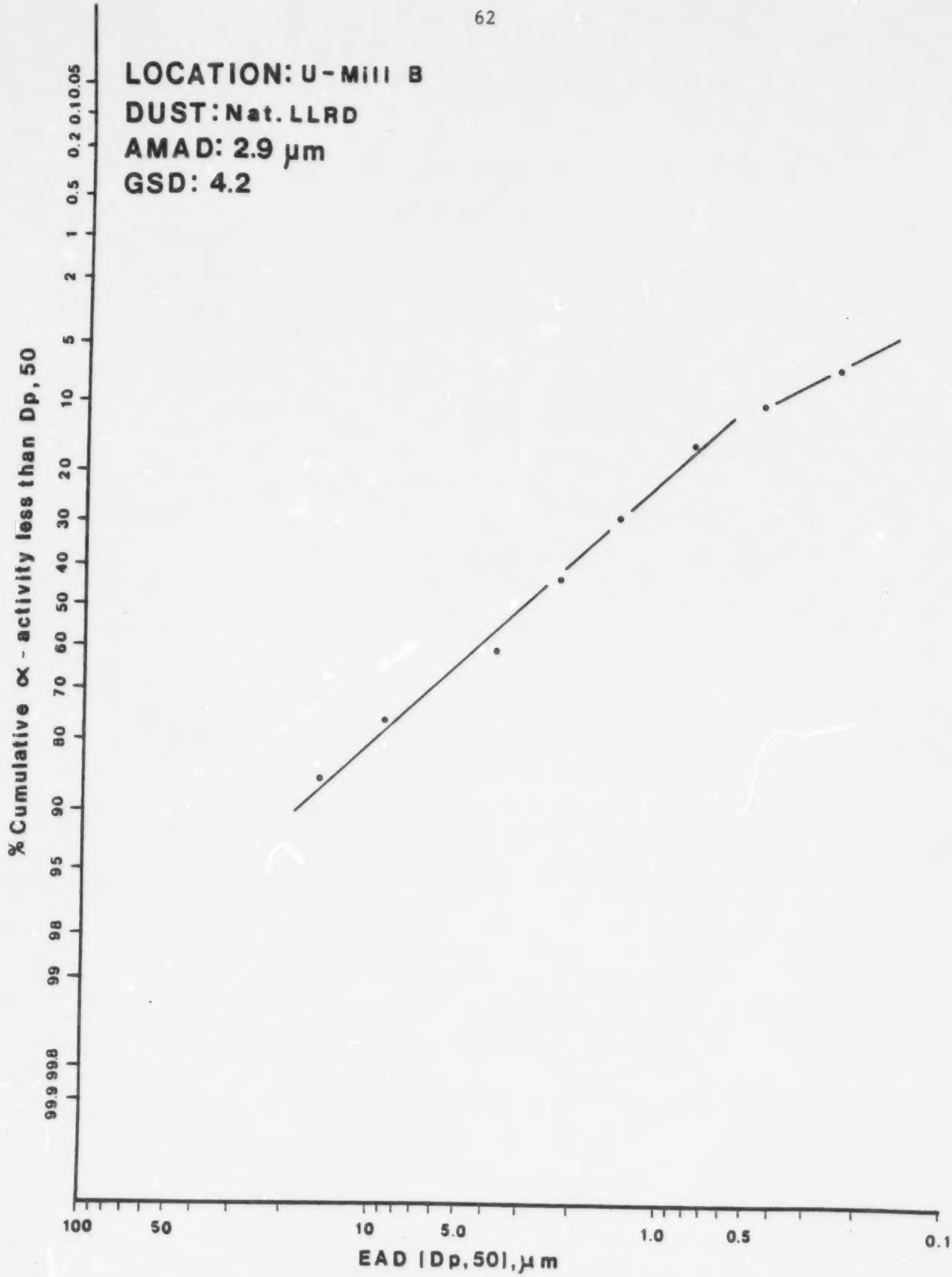


Fig. 29 - Percentage cumulative α-particle activity versus EAD measured with the Sierra 210 during the lime slaking operation.

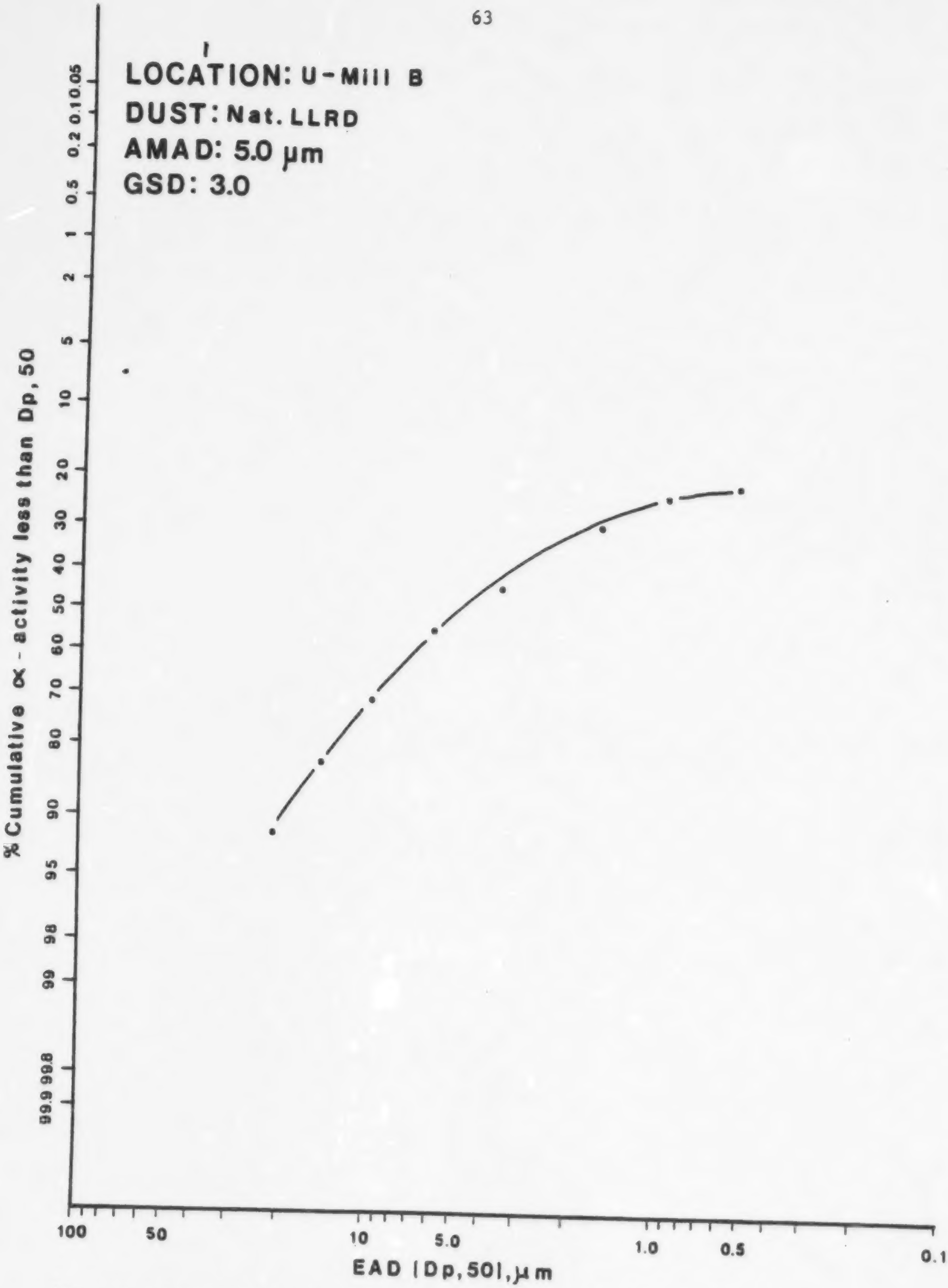


Fig. 30 - Percentage cumulative α-particle activity versus EAD measured with the Marple 290 during the lime slaking operation.

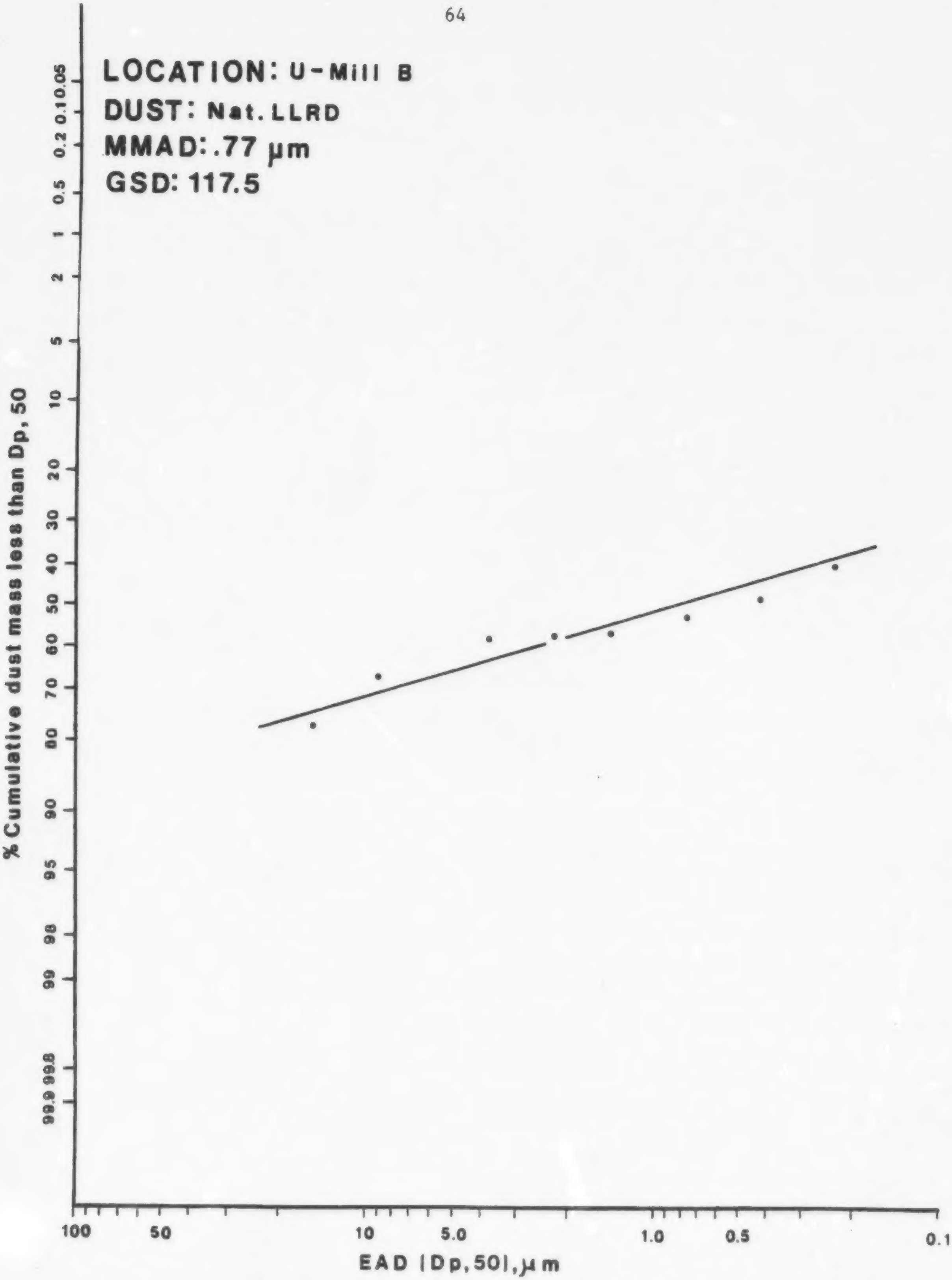


Fig. 31 - Percentage cumulative dust mass versus EAD measured with the Sierra 210 during the yellowcake packaging operation.

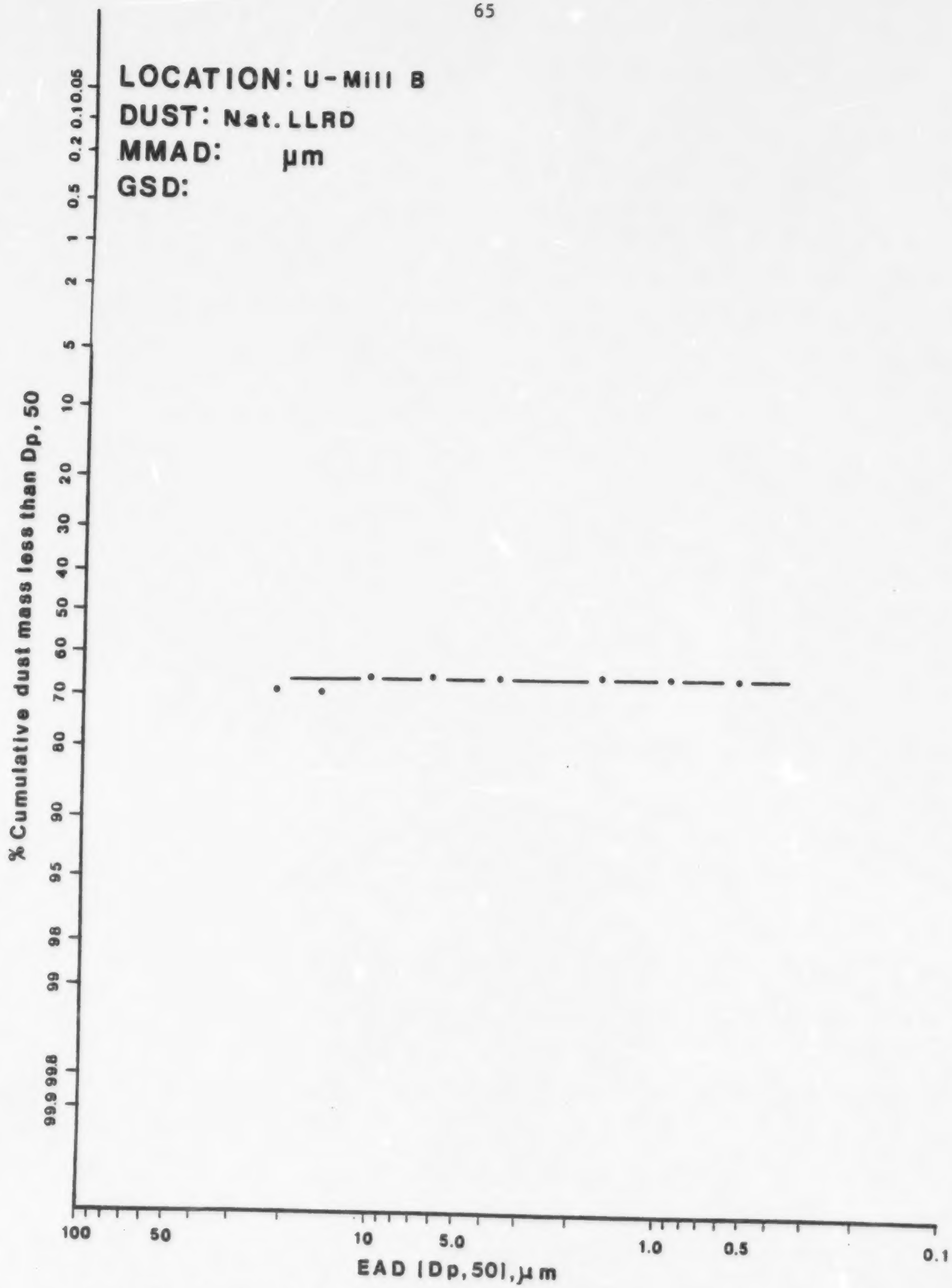


Fig. 32 - Percentage cumulative dust mass versus EAD measured with the Marple 290 during the yellowcake packaging operation.

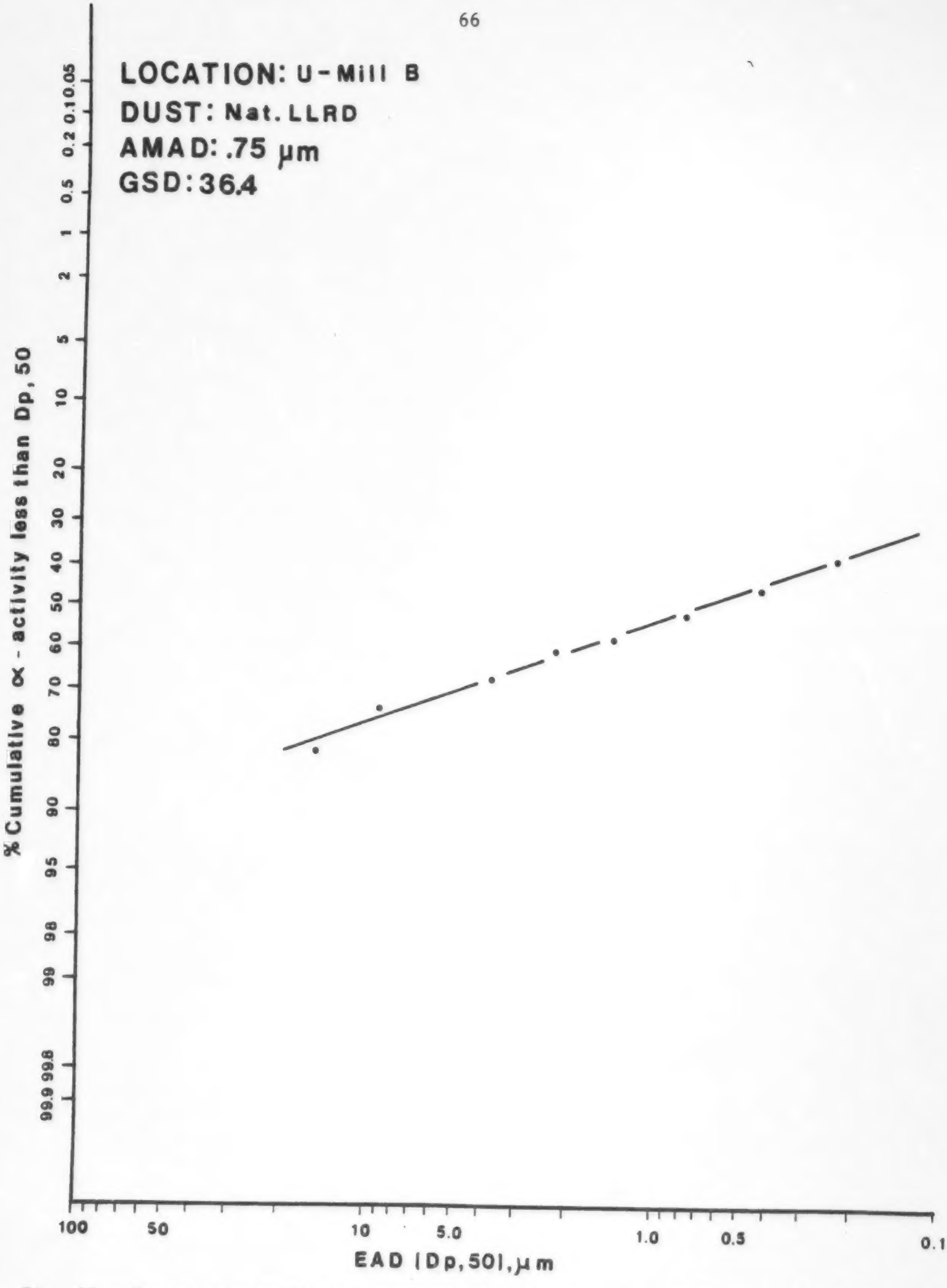


Fig. 33 - Percentage cumulative α-particle activity versus EAD measured with the Sierra 210 during the yellowcake packaging operation.

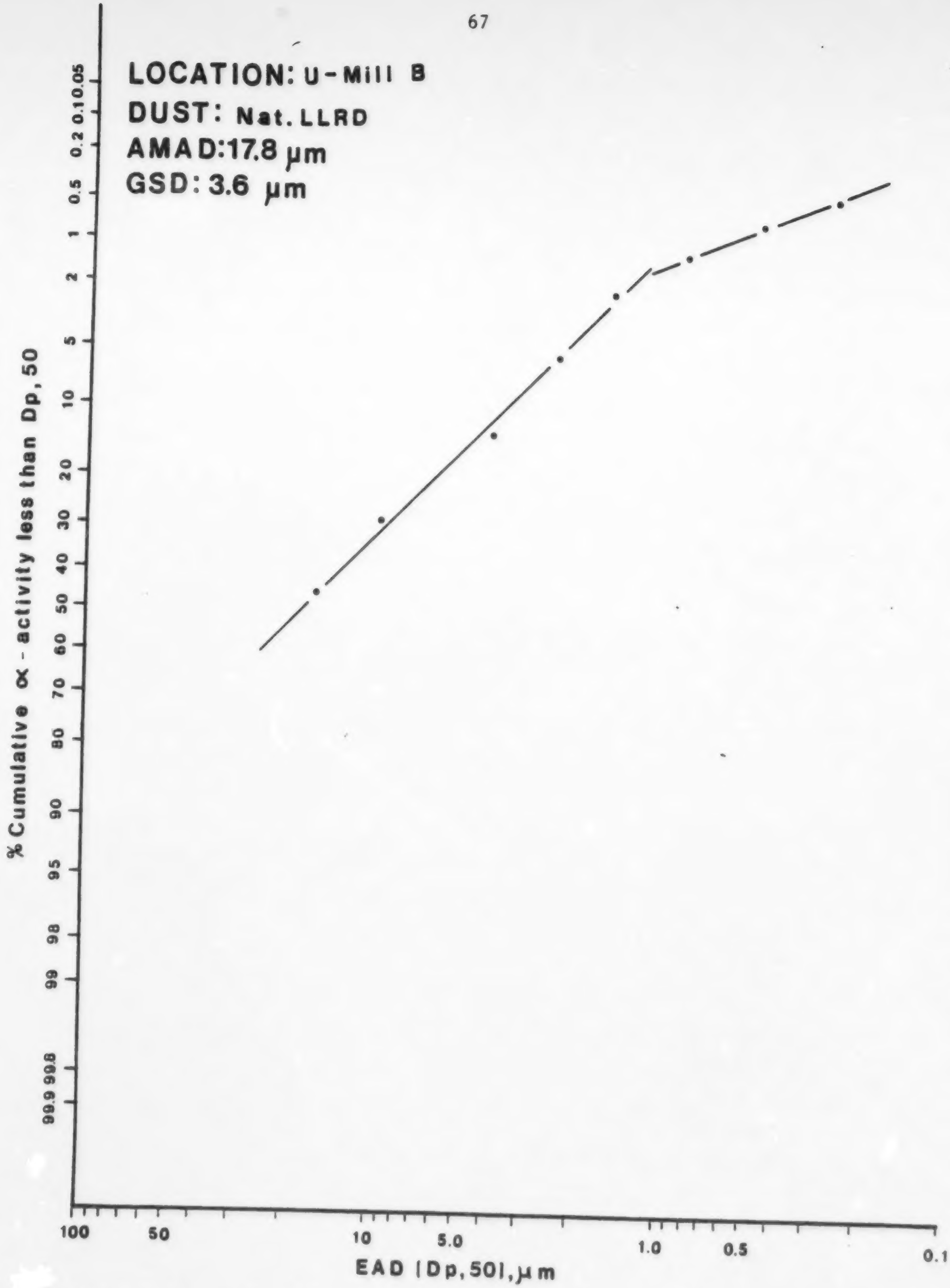


Fig. 34 - Percentage cumulative α-particle activity versus EAD measured with the Sierra 210 during the yellowcake packaging operation.

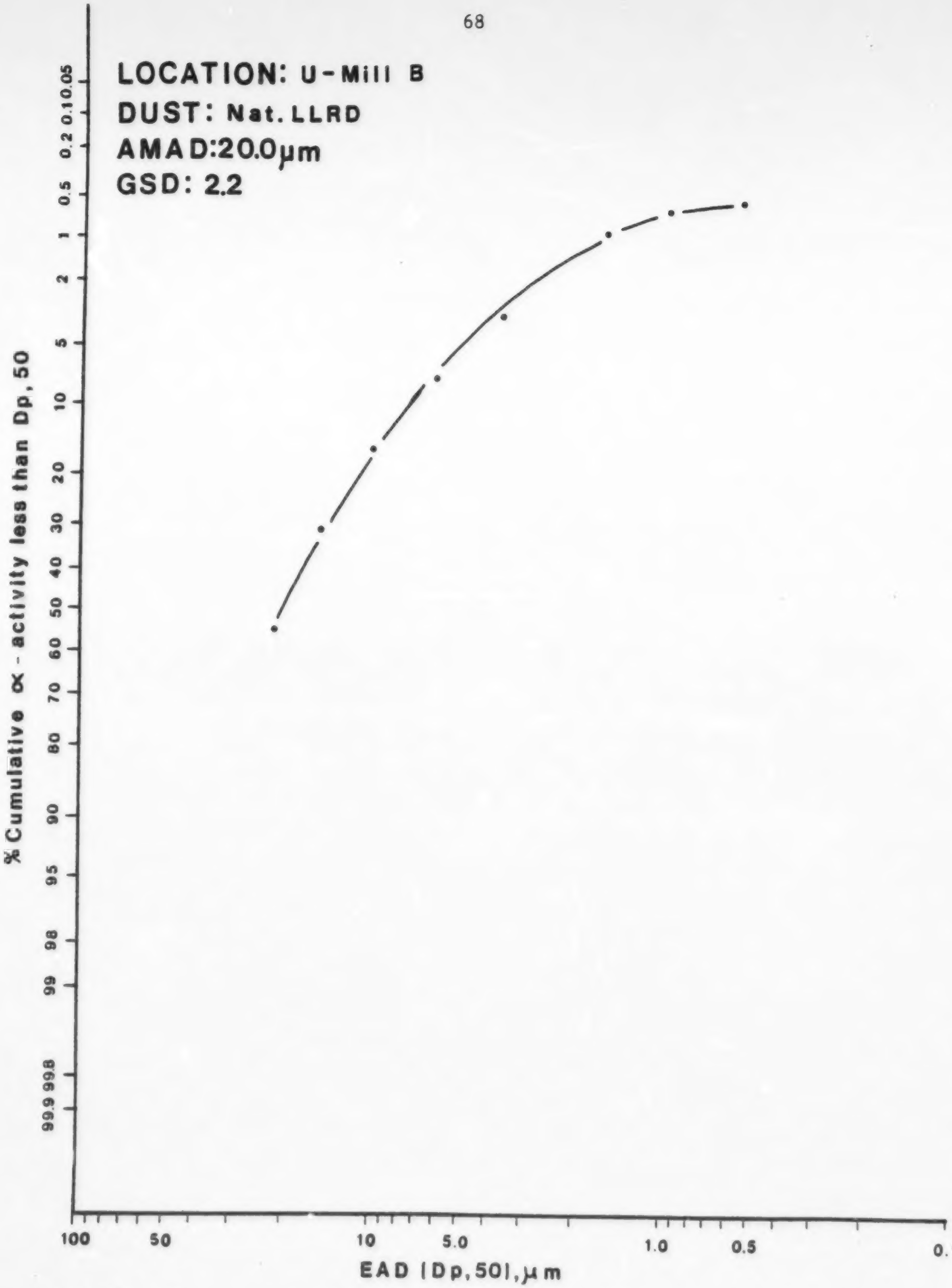


Fig. 35 - Percentage cumulative α-particle activity versus EAD measured with the Marple 290 during the yellowcake packaging operation.

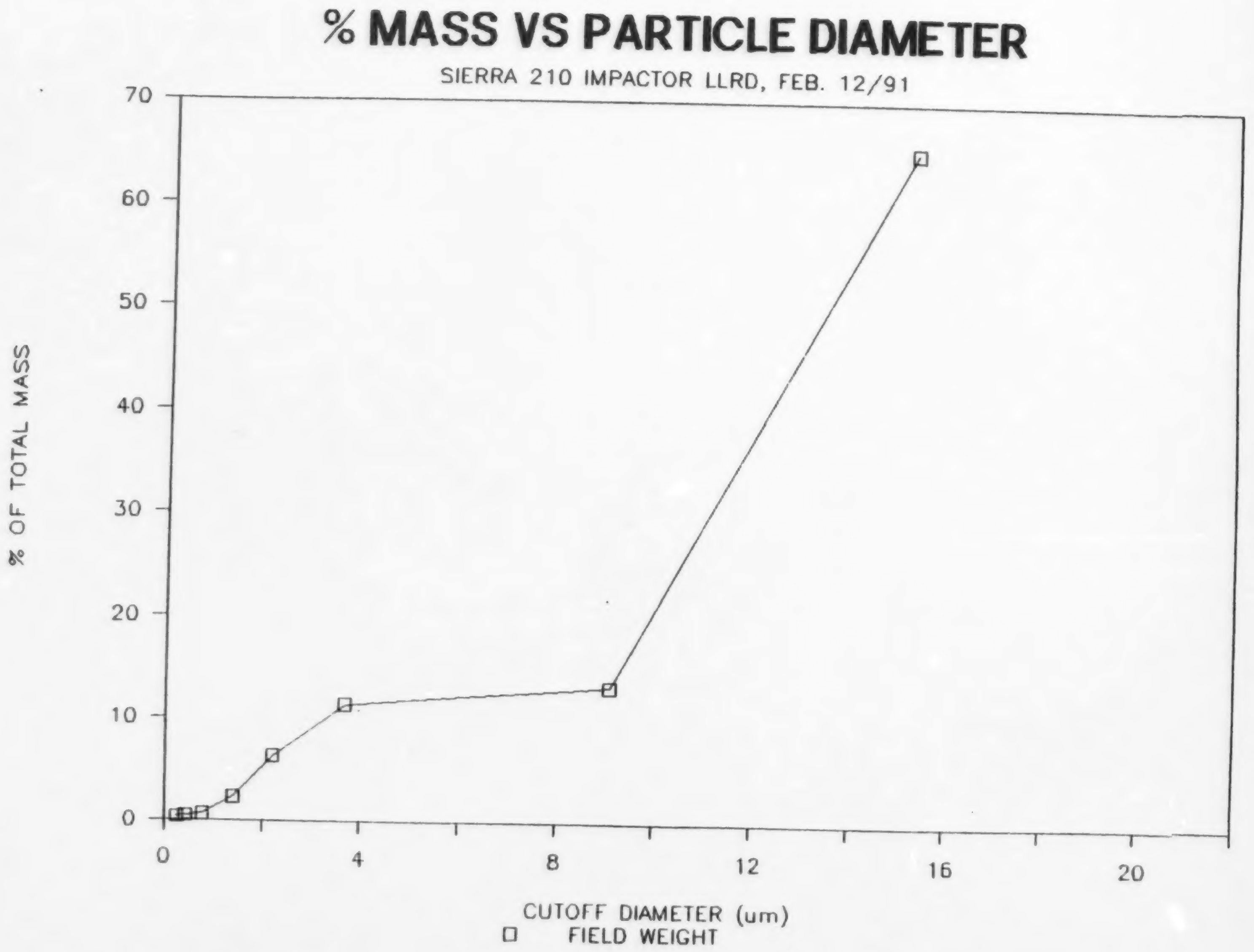


Fig. 36 - Percentage of total mass versus particle cut-off diameter at the crusher/conveyor belt transfer point.

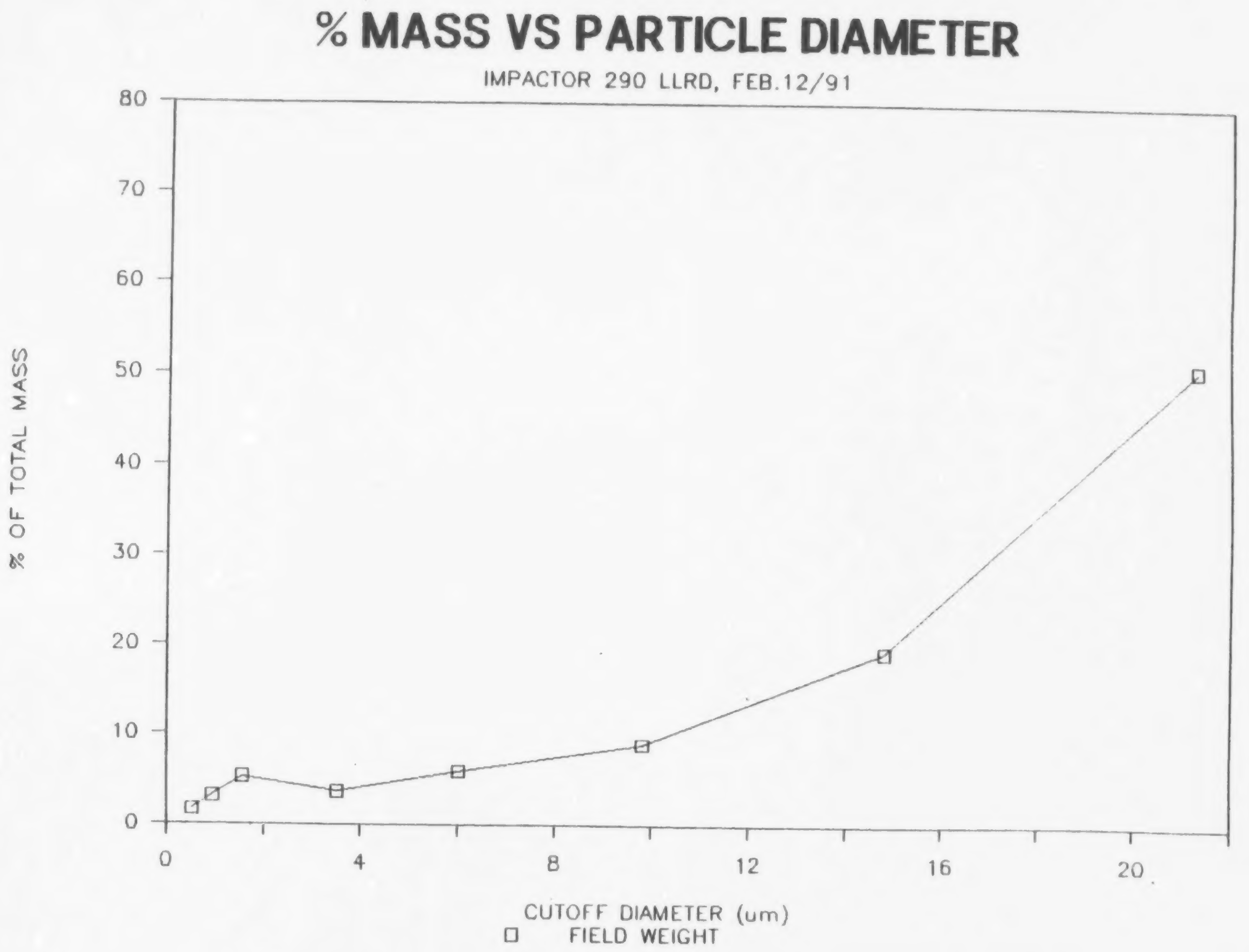


Fig. 37 - Percentage of total mass versus particle cut-off diameter at the crusher/conveyor belt transfer point.

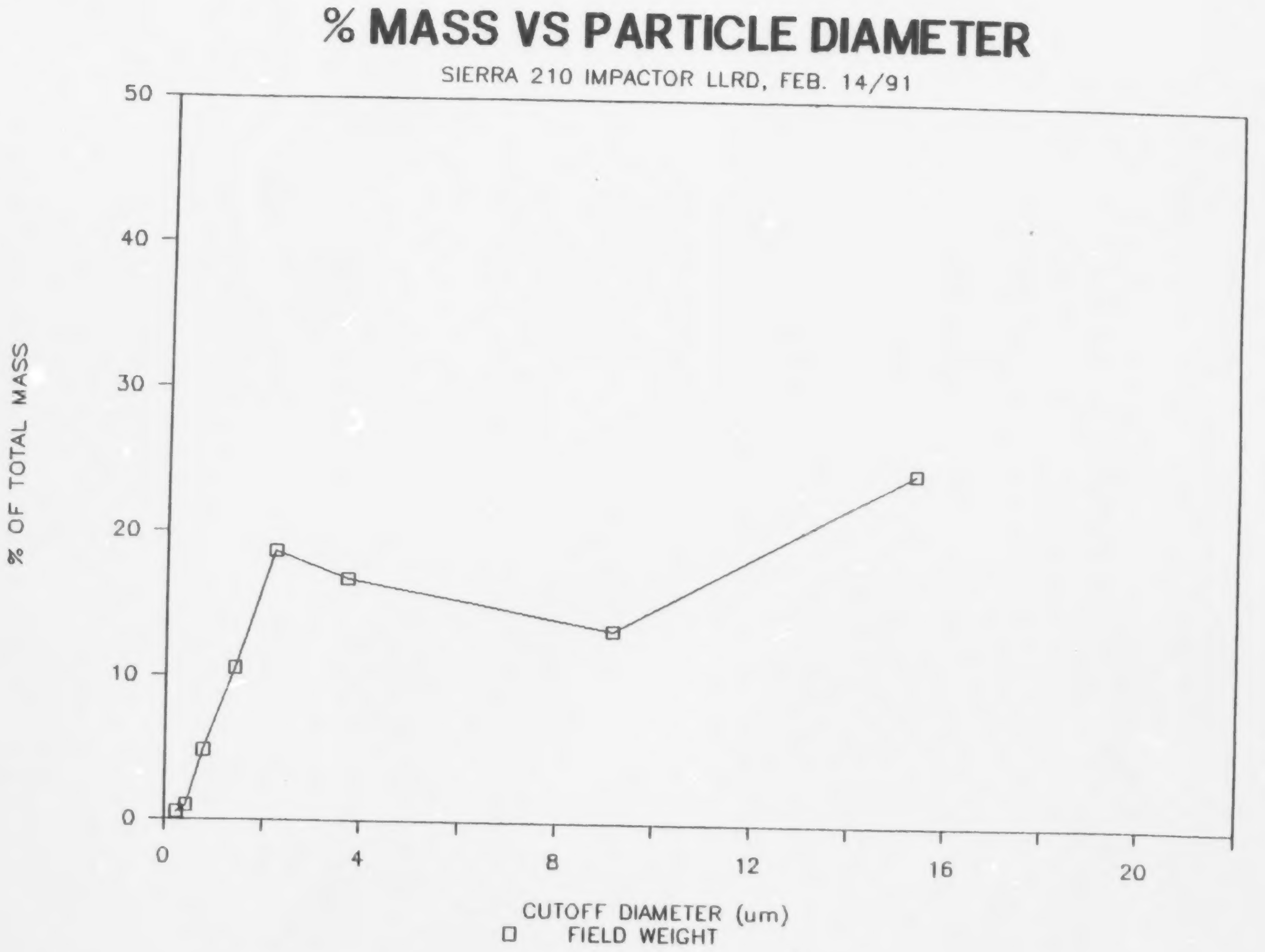


Fig. 38 - Percentage of total mass versus particle cut-off diameter for the ball milling operation.

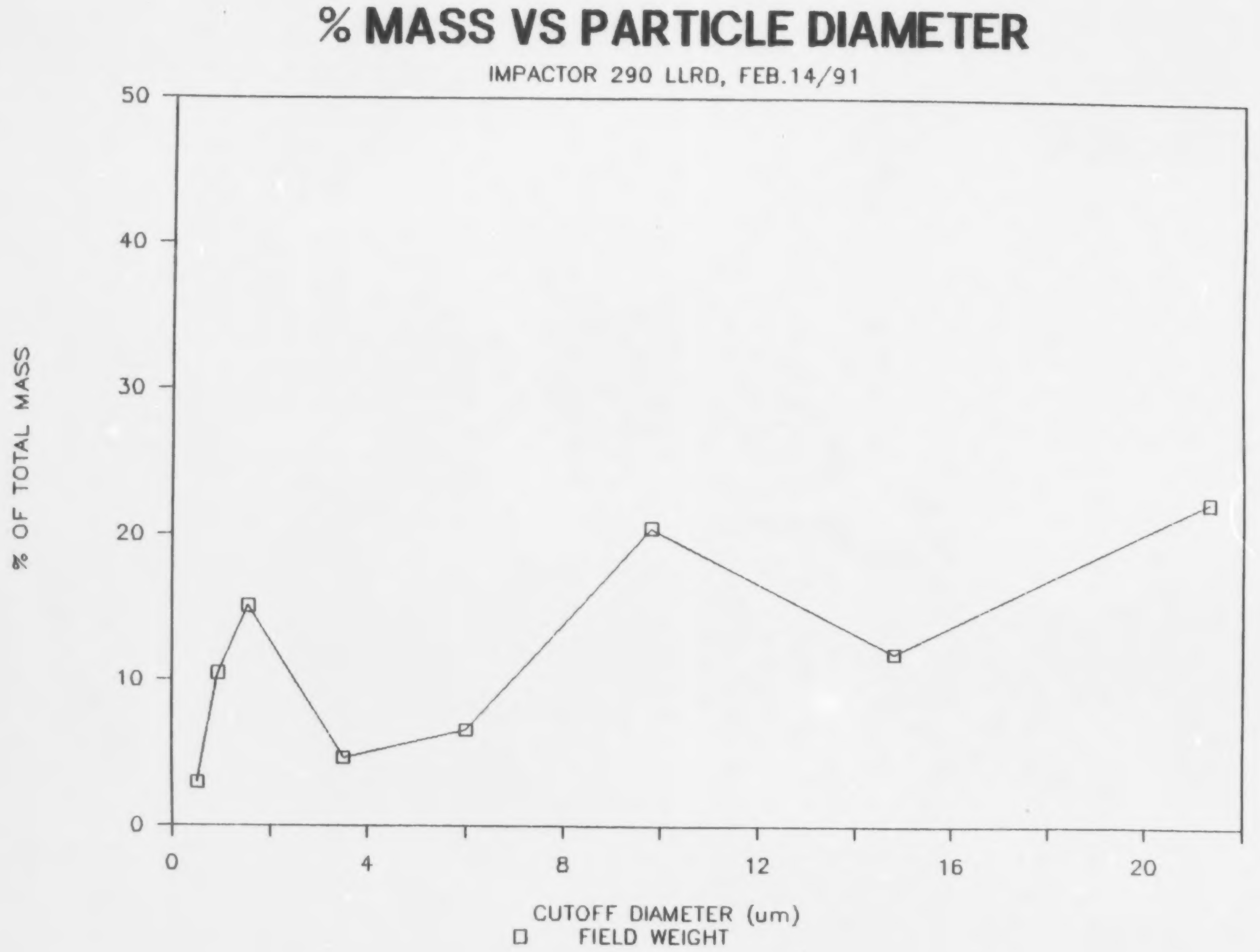


Fig. 39 - Percentage of total mass versus particle cut-off diameter for the ball milling operation.

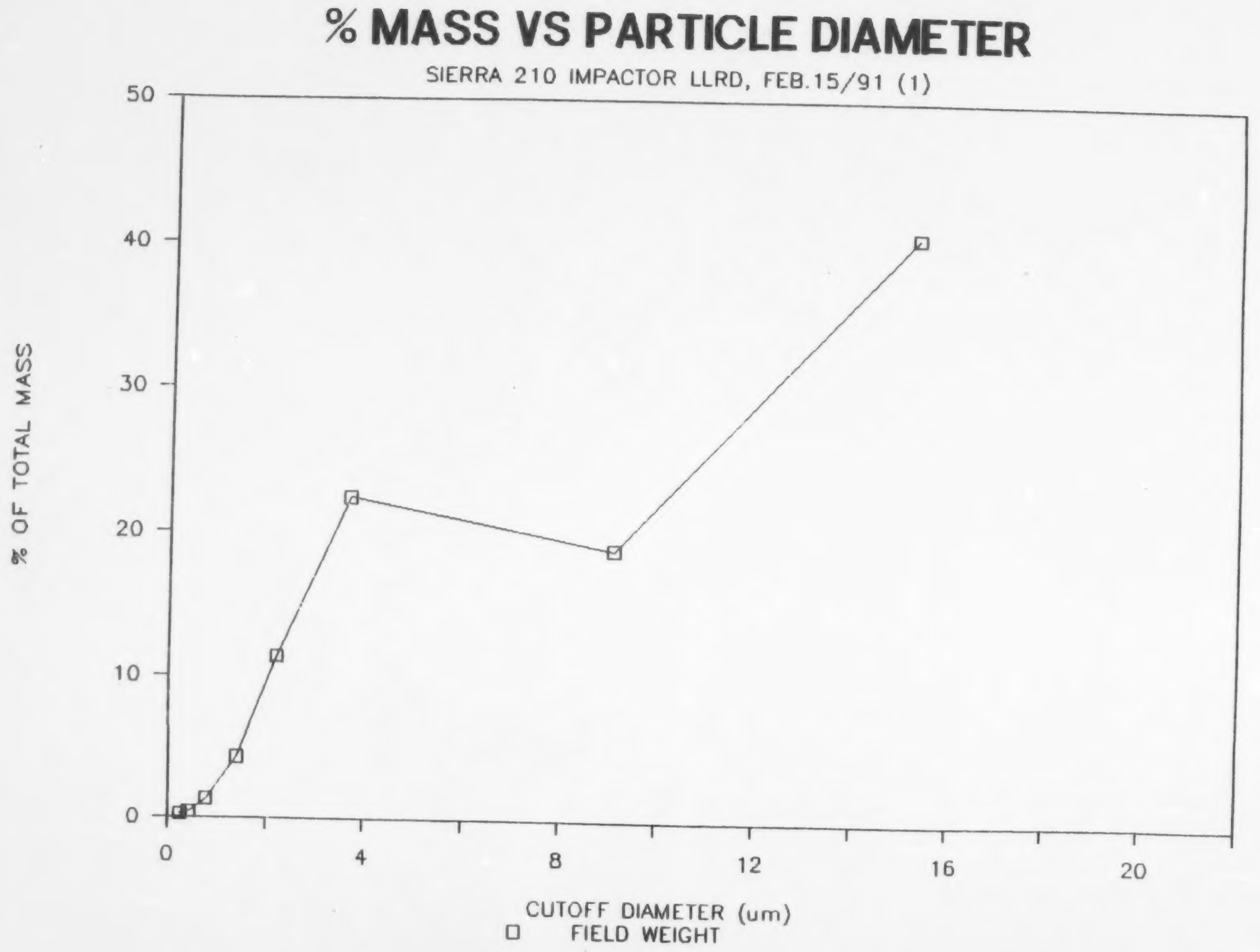


Fig. 40 - Percentage of total mass versus particle cut-off diameter for the cone crushing operation.

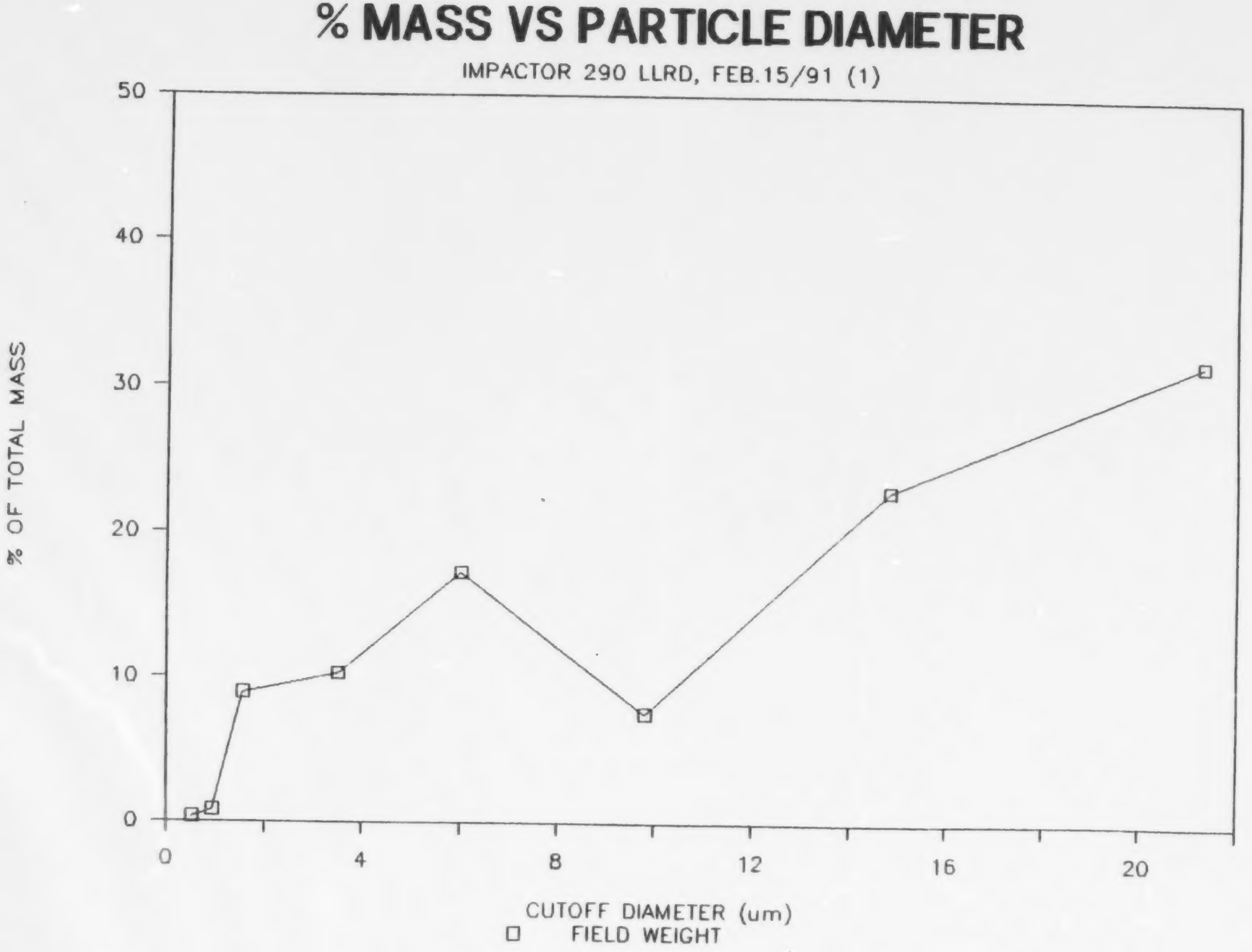


Fig. 41 - Percentage of total mass versus particle cut-off diameter for the cone crushing operation.

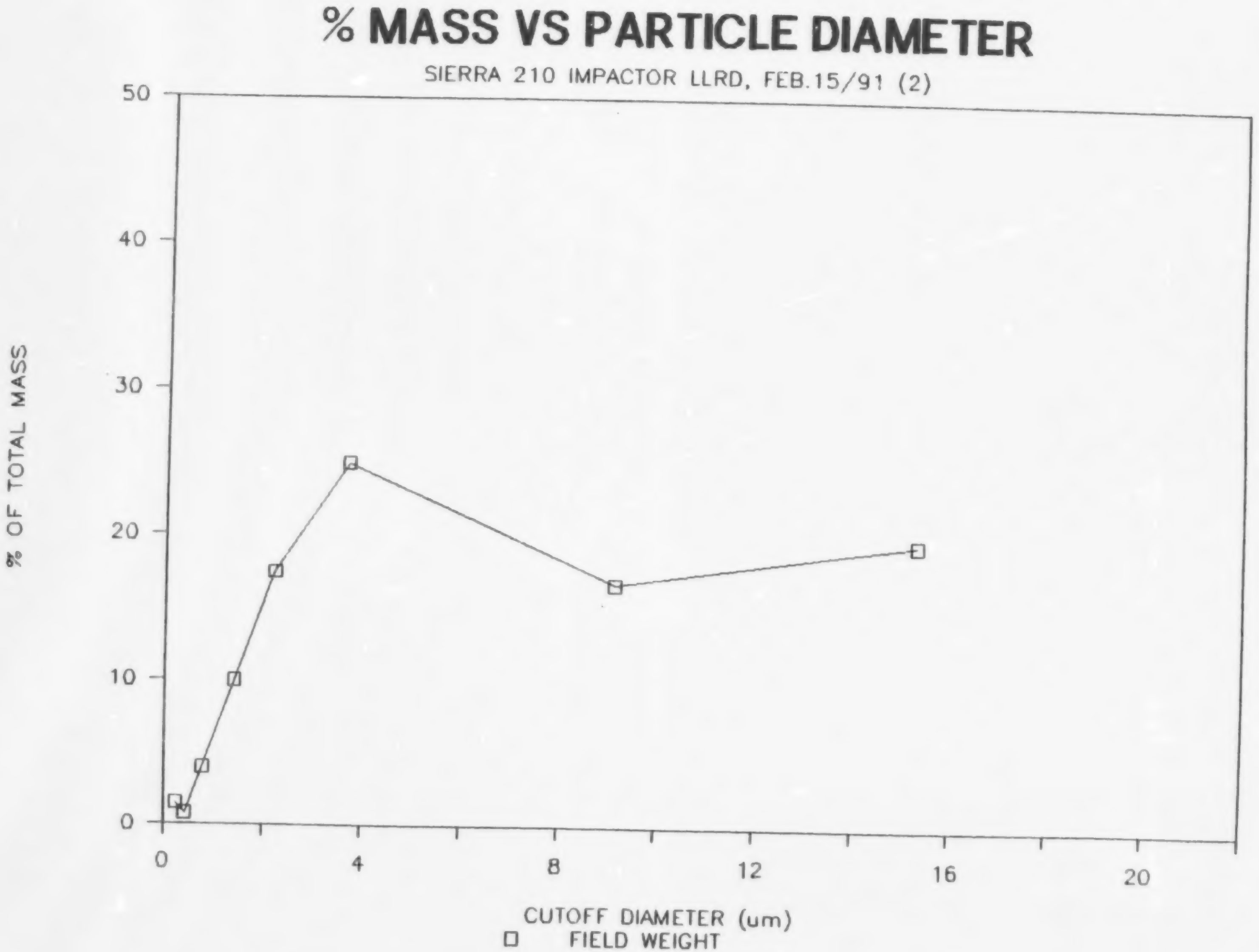


Fig. 42 - Percentage of total mass versus particle cut-off diameter for the yellowcake precipitation operation.

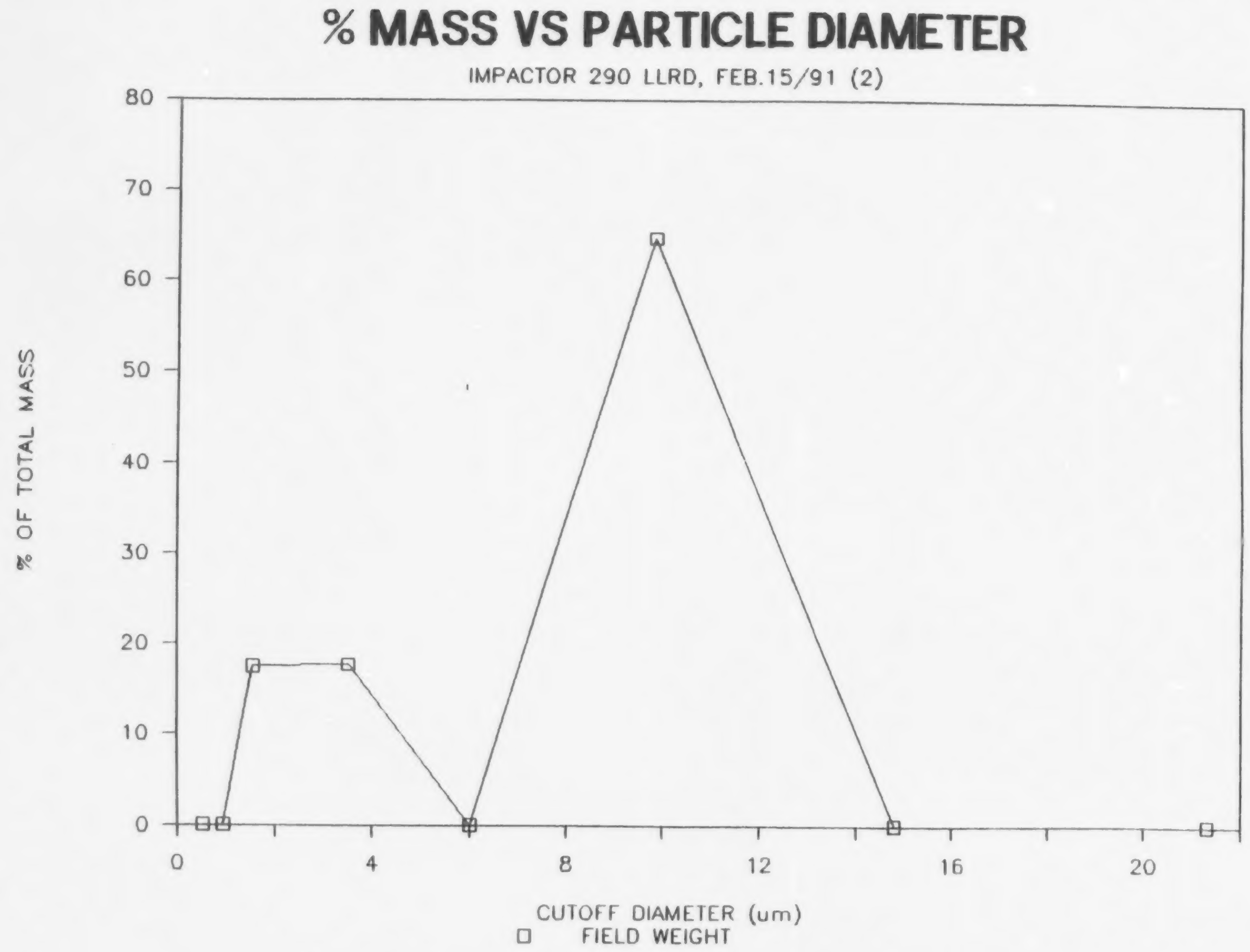


Fig. 43 - Percentage total mass versus particle cut-off diameter for the yellowcake precipitation operation.

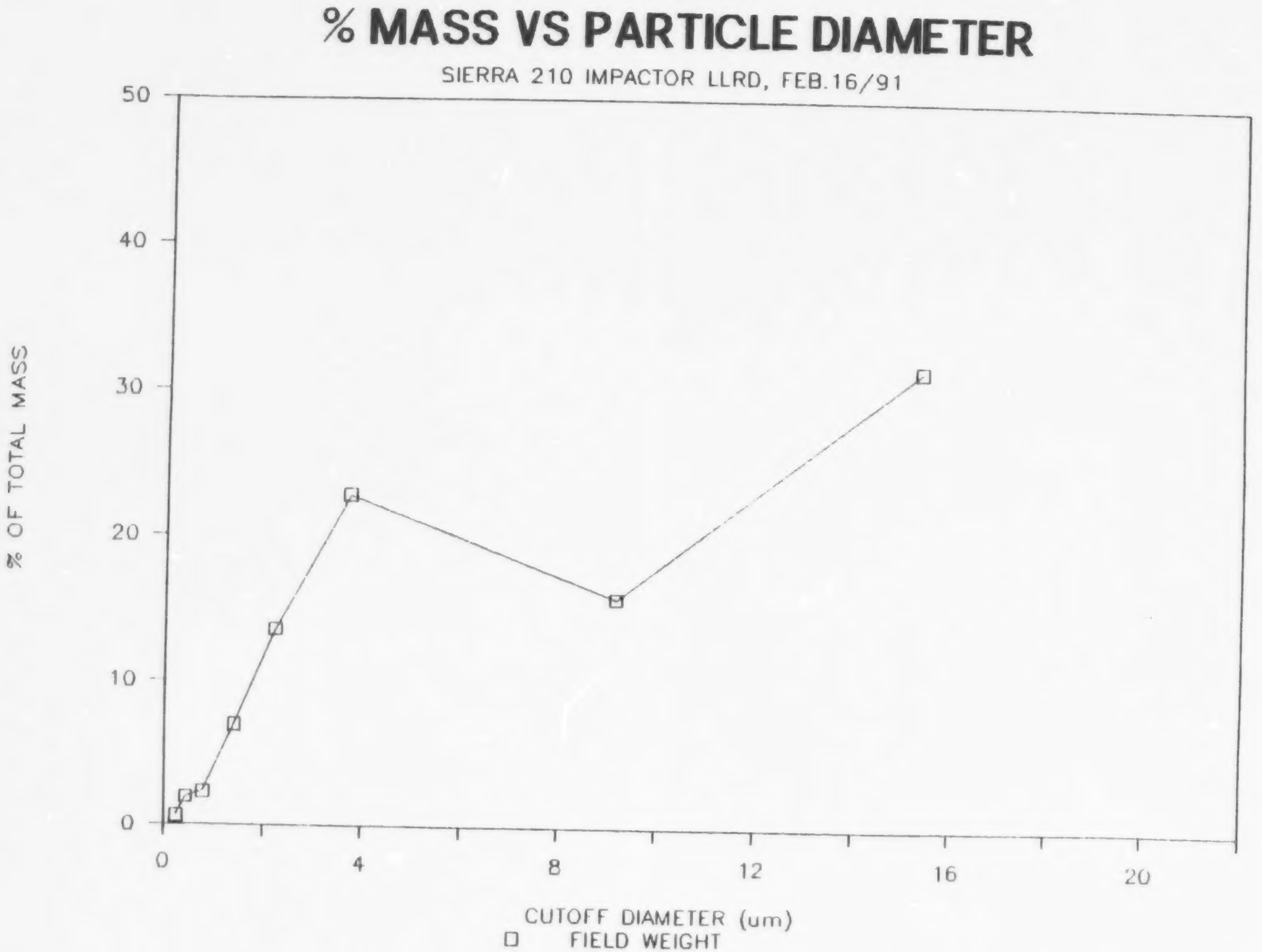


Fig. 44 - Percentage total mass versus particle cut-off diameter at the hopper/conveyor belt/ball mill area.

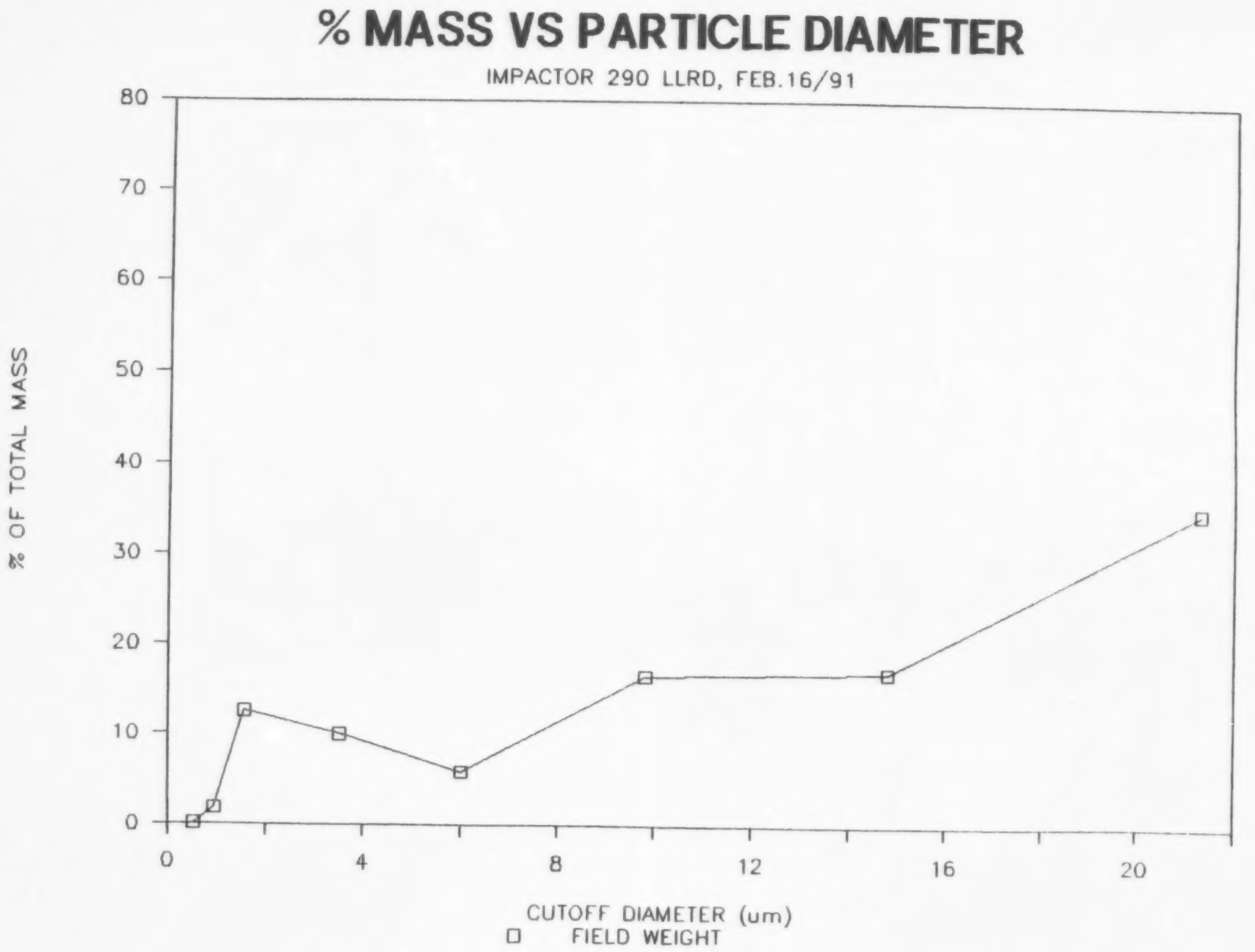


Fig. 45 - Percentage total mass versus particle cut-off diameter at the hopper/conveyor belt/ball mill area.

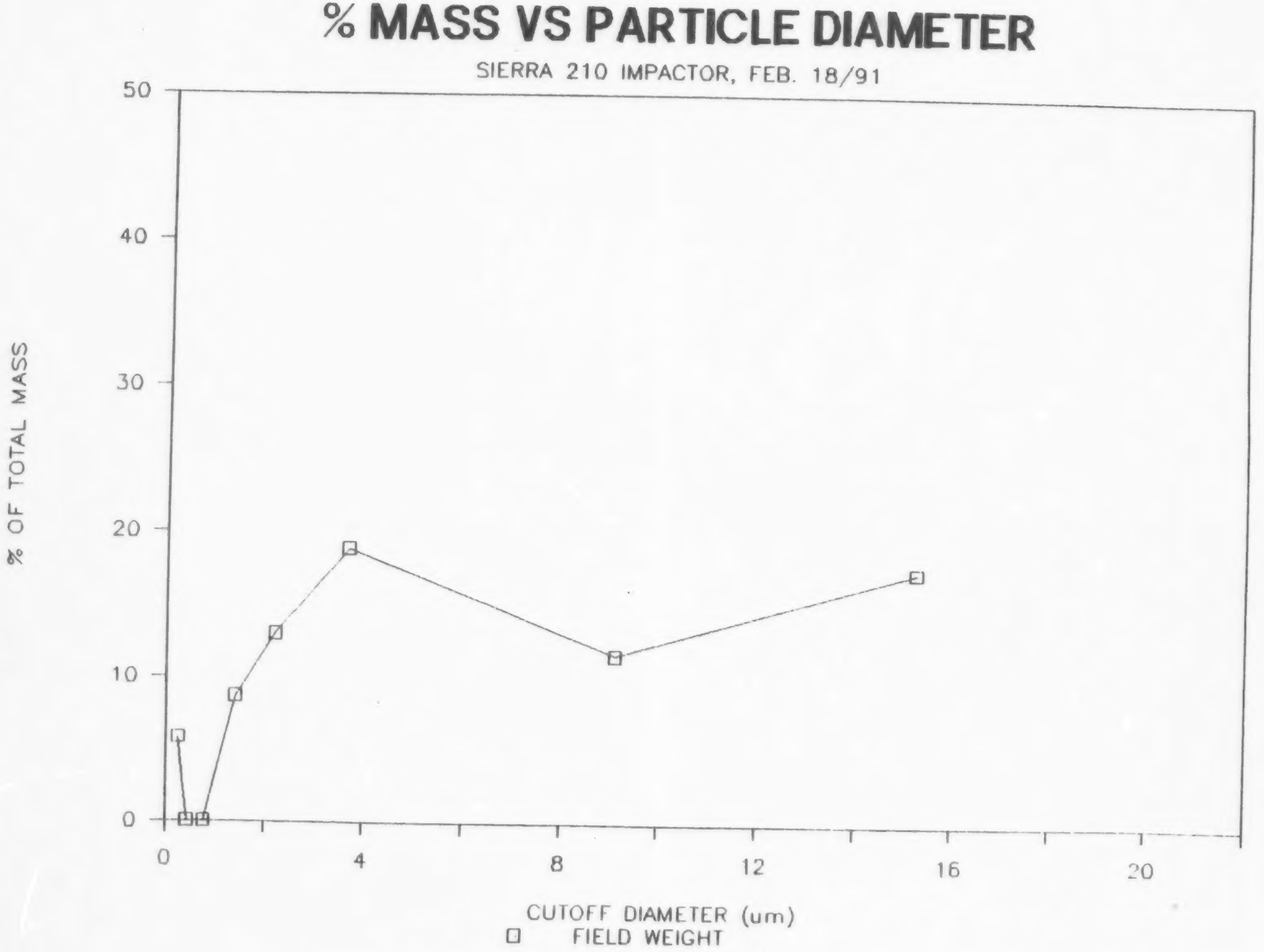


Fig. 46 - Percentage total mass versus particle cut-off diameter for the S.A.G. milling operation.

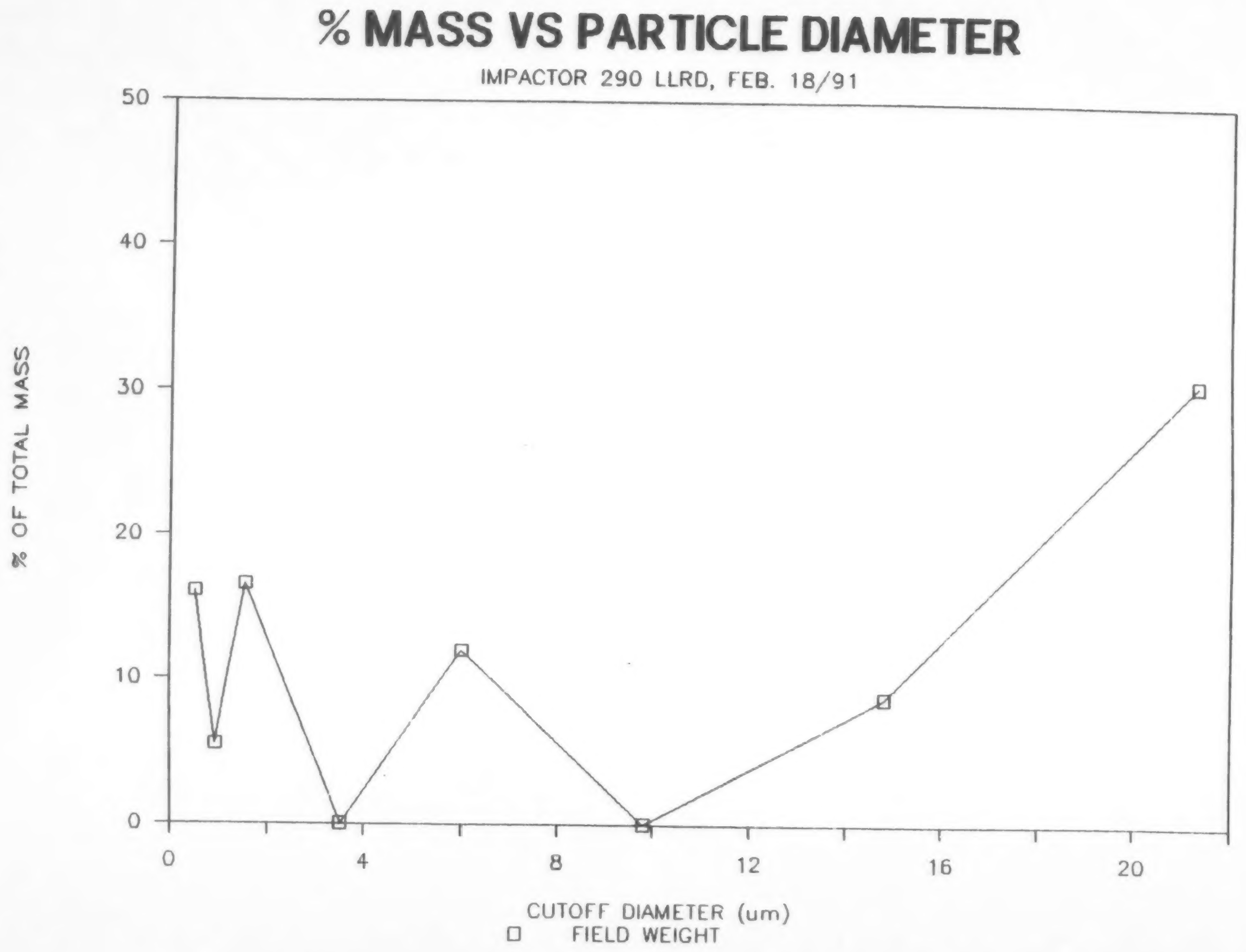


Fig. 47 - Percentage total mass versus particle cut-off diameter for the S.A.G. milling operation.

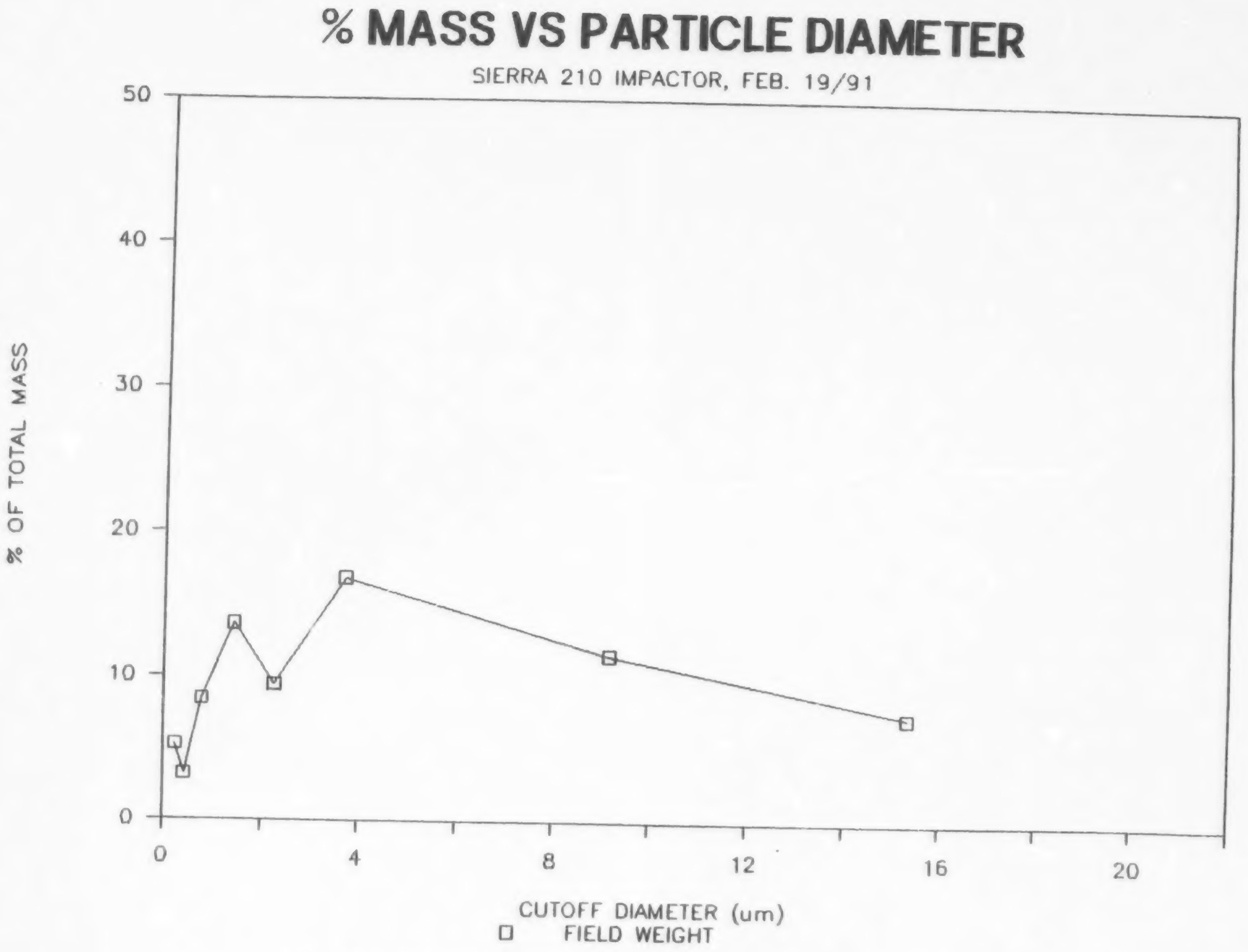


Fig. 48 - Percentage of total mass versus particle cut-off diameter for the lime slaking operation.

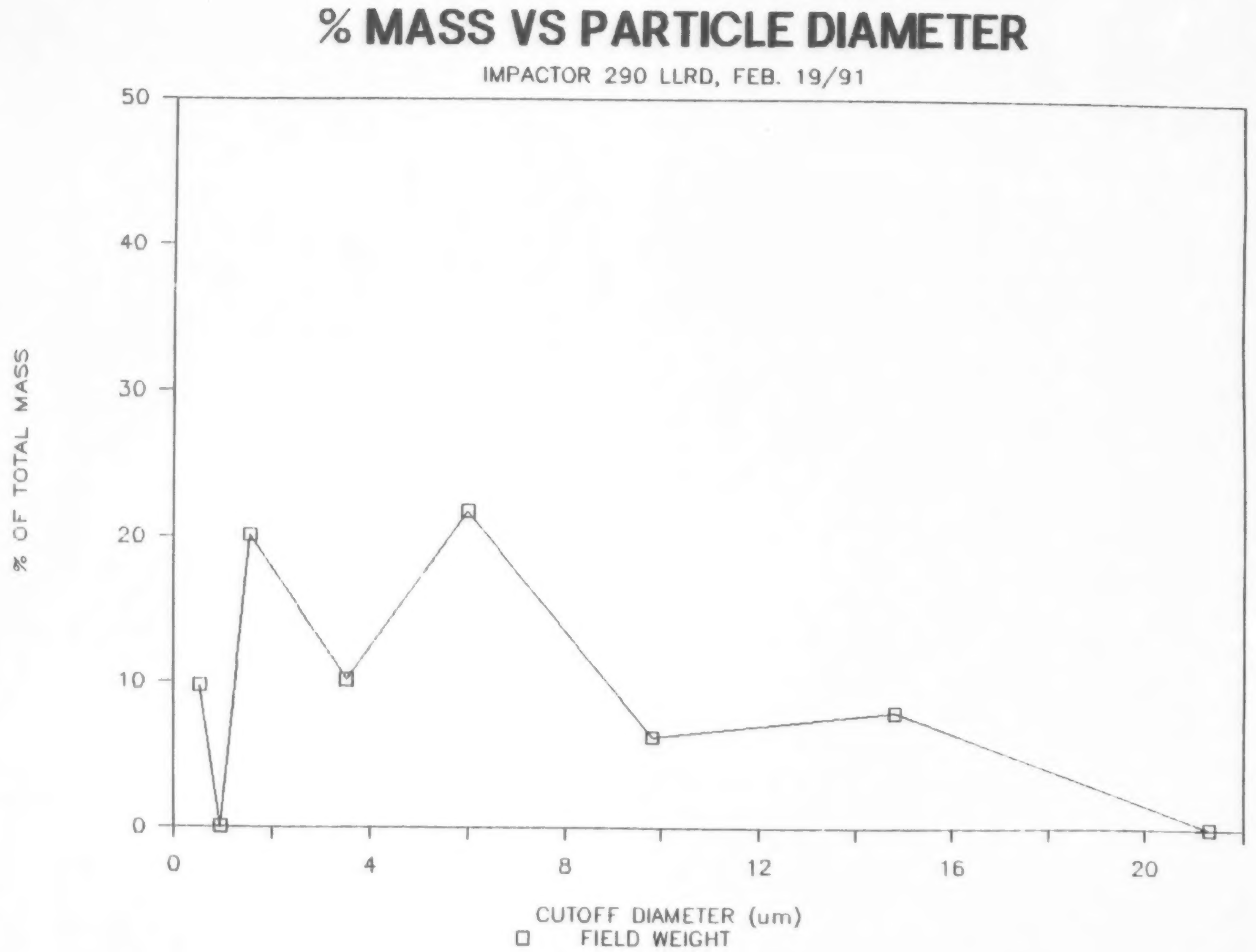


Fig. 49 - Percentage total mass versus particle cut-off diameter for the lime slaking operation.

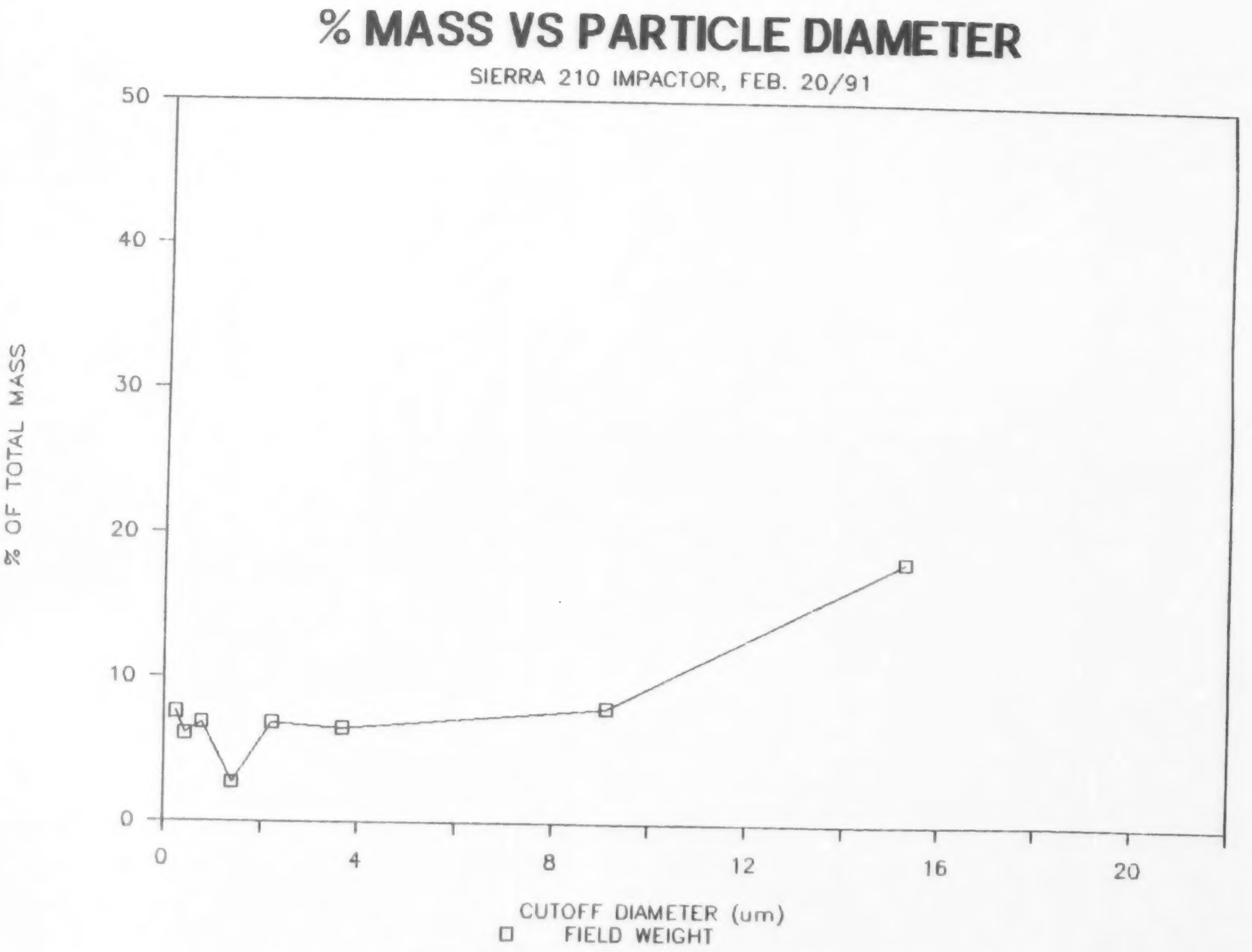


Fig. 50 - Percentage total mass versus particle cut-off diameter for the yellowcake packaging operation.

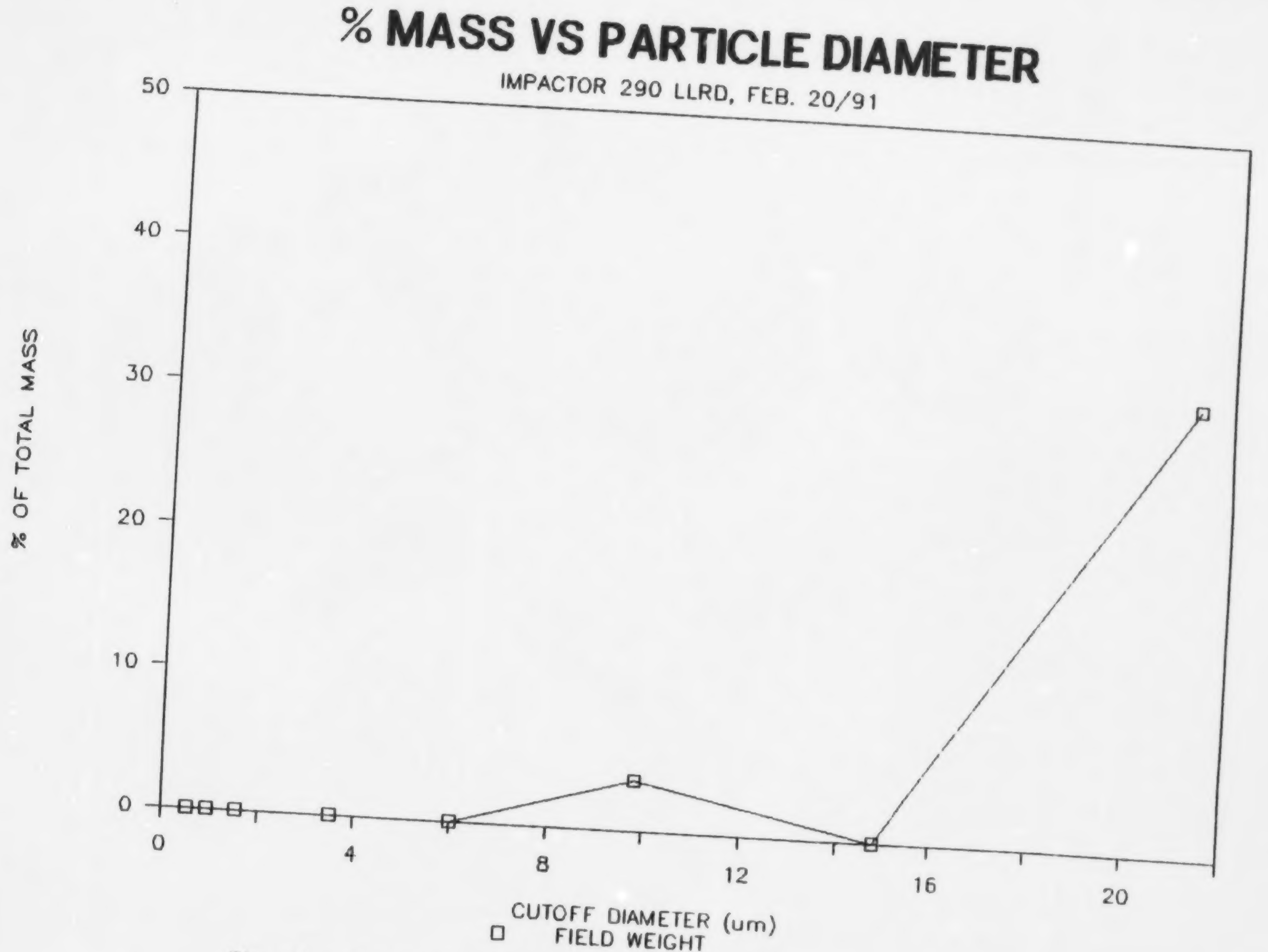


Fig. 51 - Percentage total mass versus particle cut-off diameter for the yellowcake packaging operation.

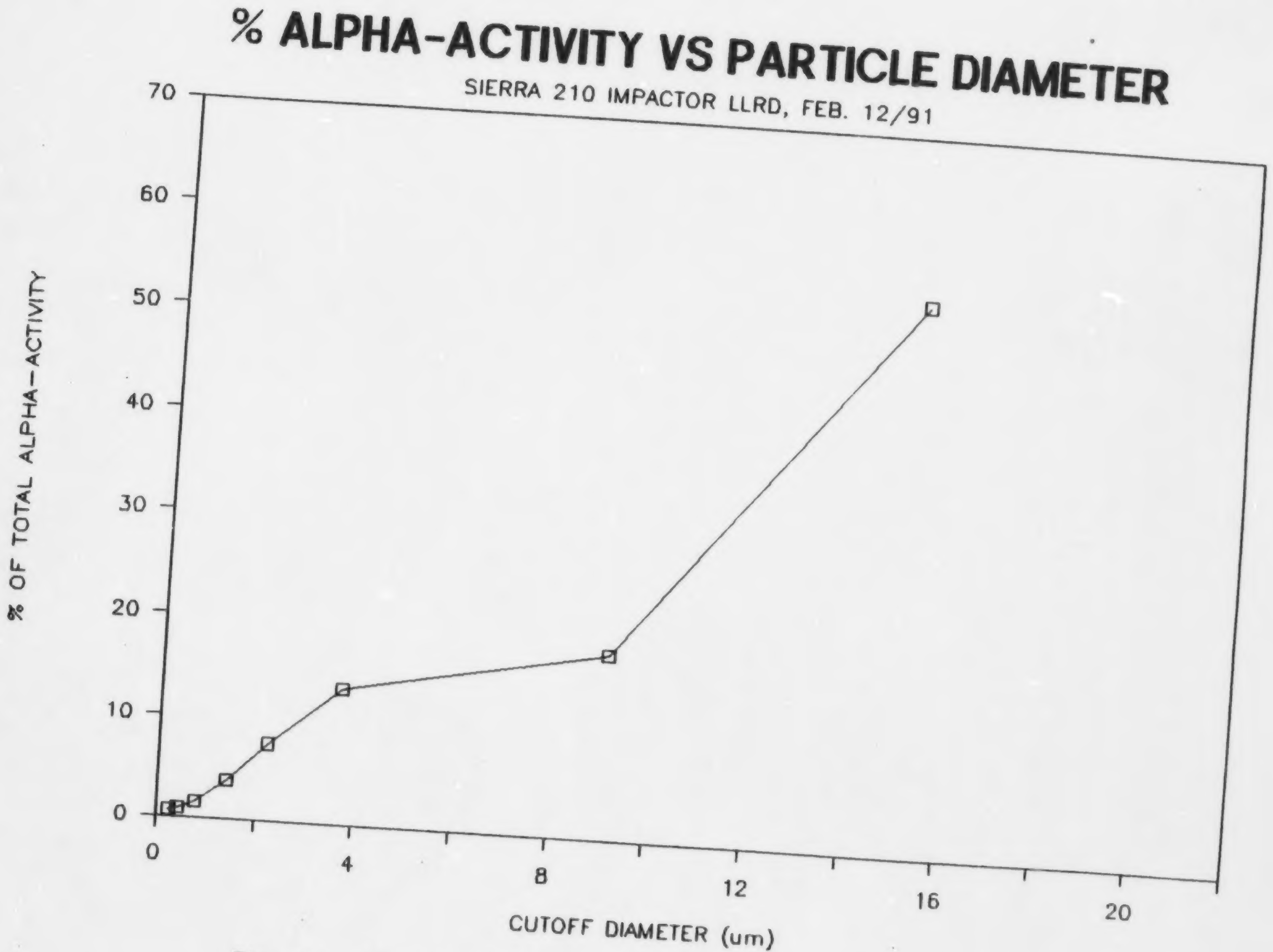


Fig. 52 - Percentage of total α-particle activity versus particle cut-off diameter at the crusher/conveyor belt transfer point.

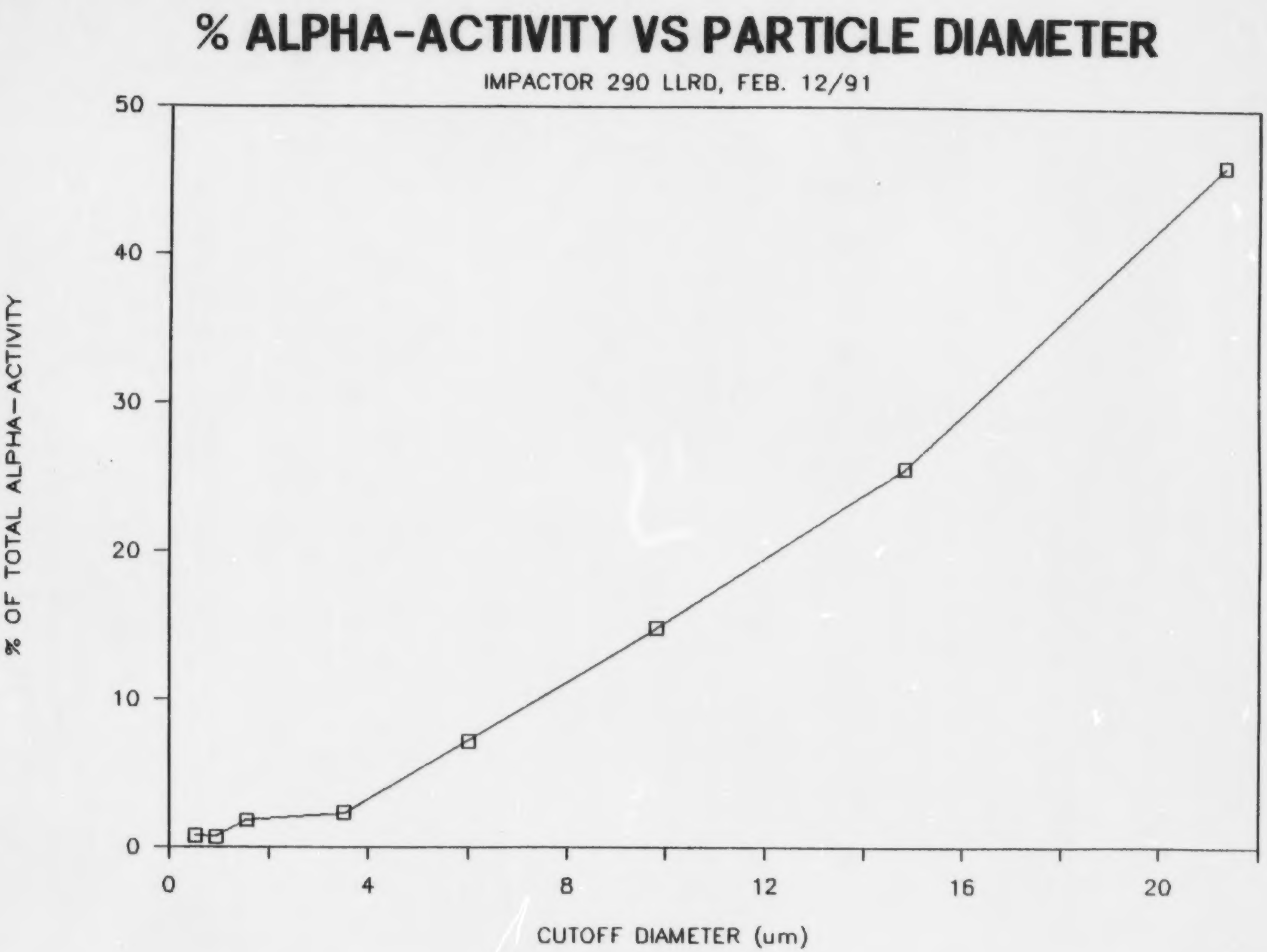


Fig. 53 - Percentage total α-particle activity versus particle cut-off diameter at the crusher/conveyor belt transfer point.

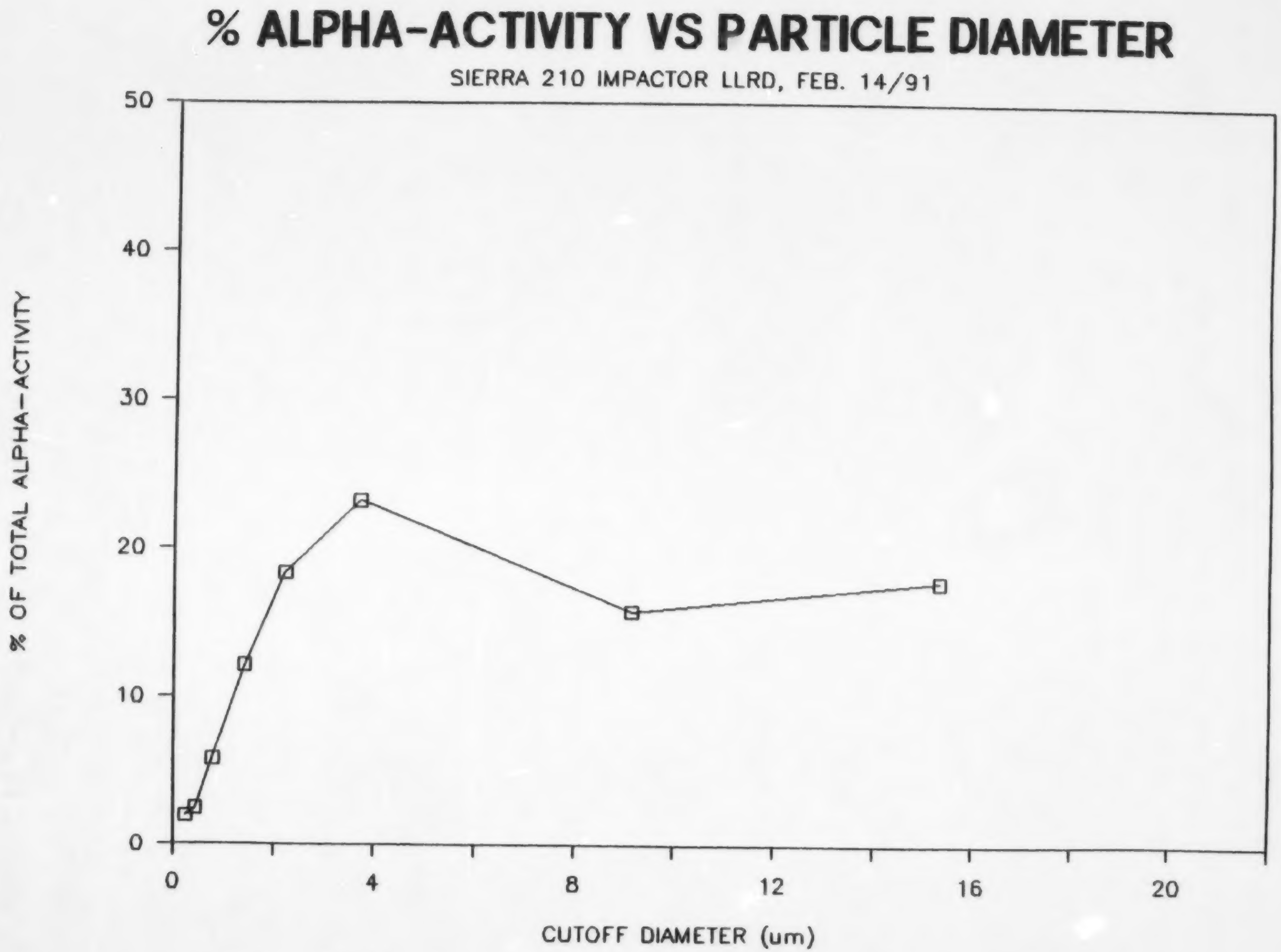


Fig. 54 - Percentage of total α-particle activity versus particle cut-off diameter for the ball milling operation.

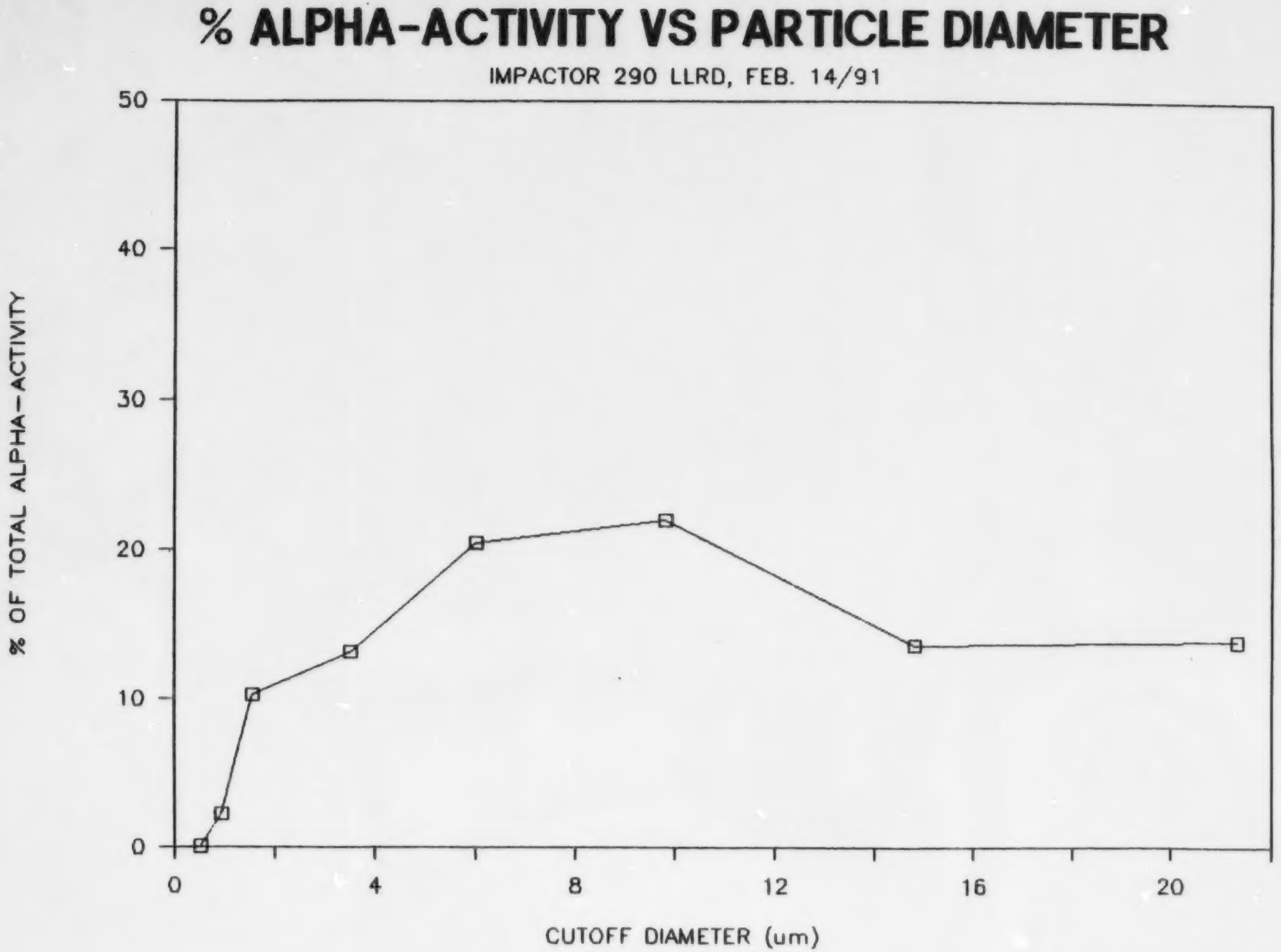


Fig. 55 - Percentage total α-particle activity versus particle cut-off diameter for the ball milling operation.

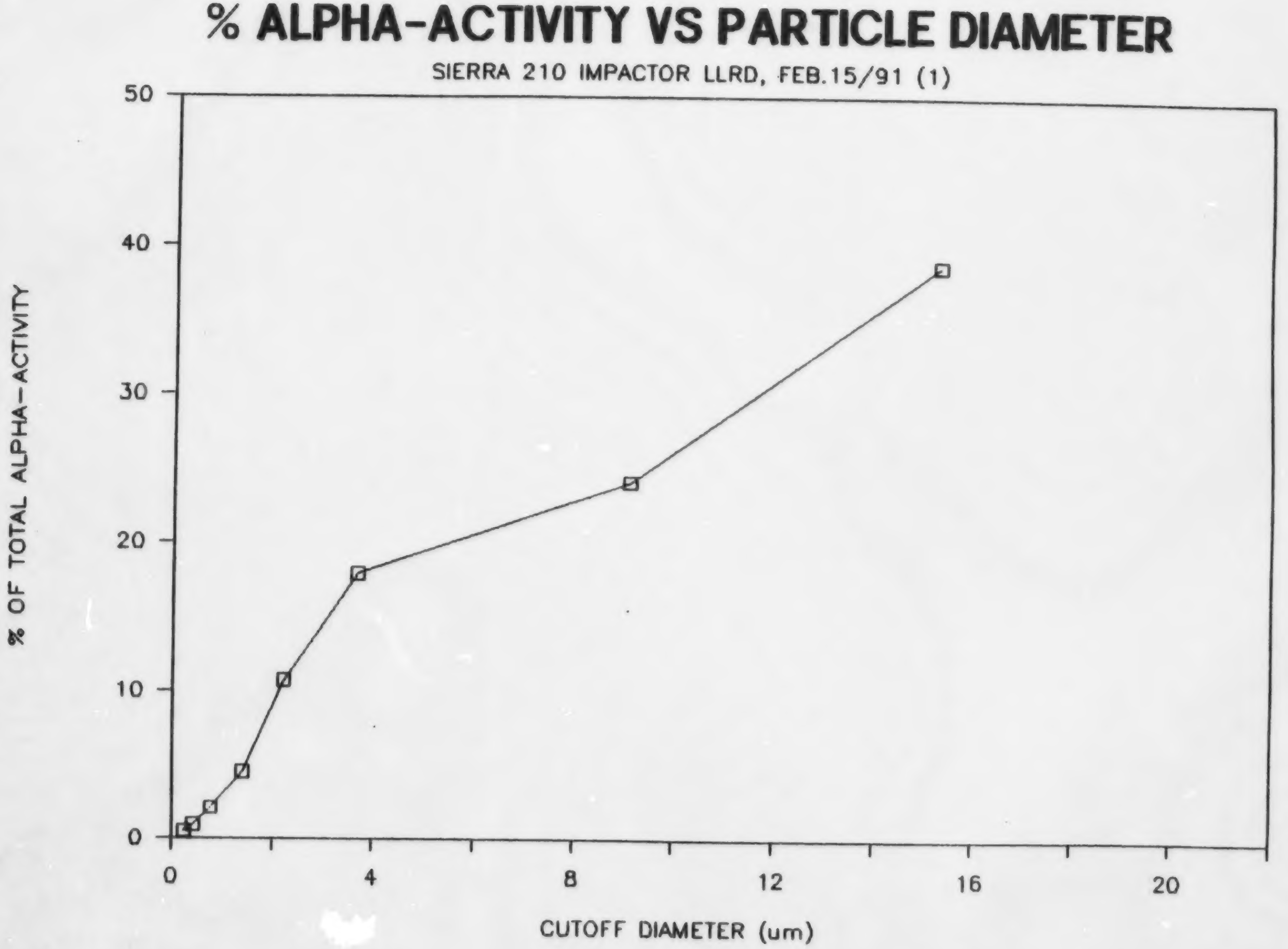


Fig. 56 - Percentage total α-particle activity versus particle cut-off diameter for the cone crushing operation.

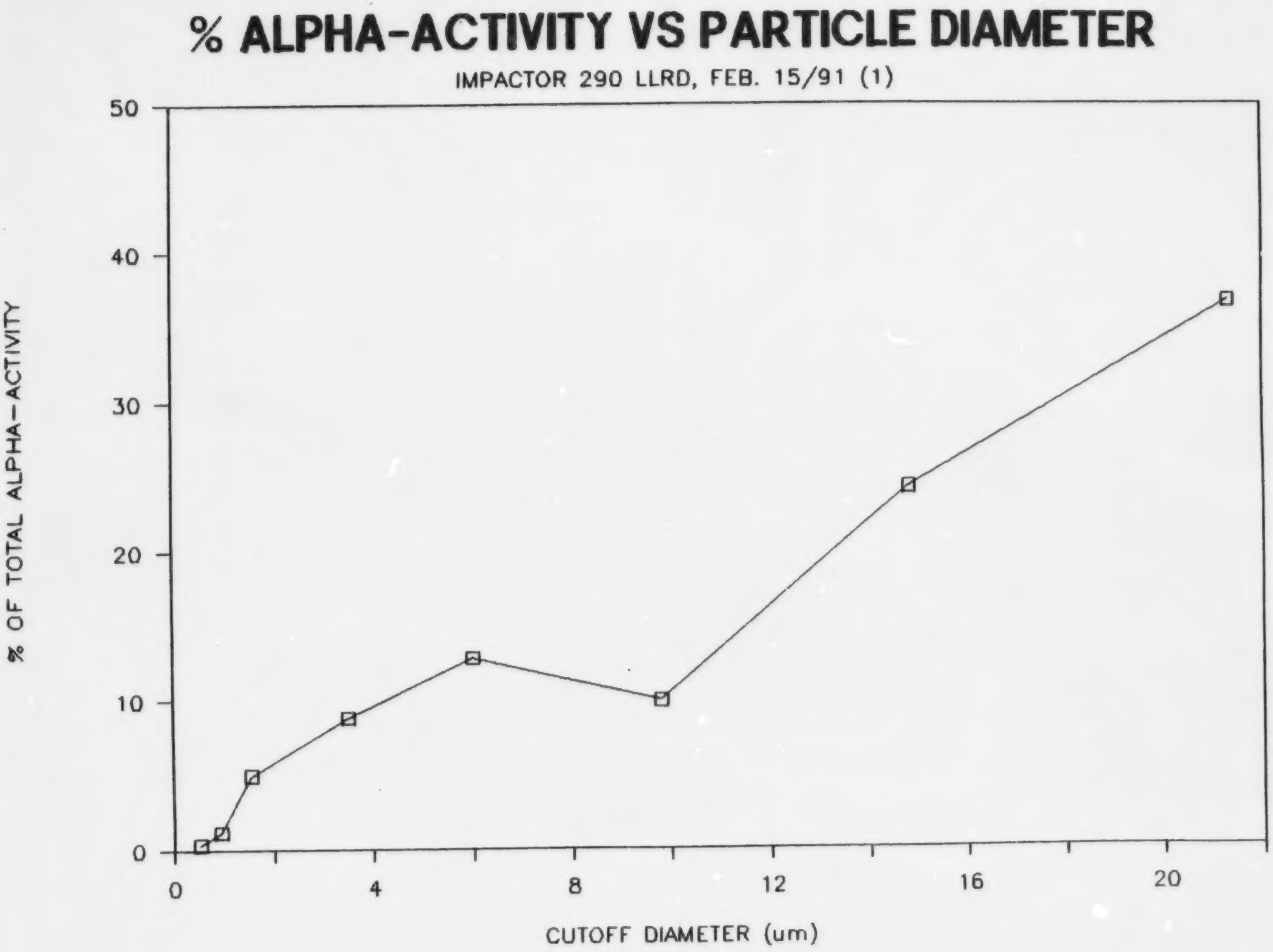


Fig. 57 - Percentage total α-particle activity versus particle cut-off diameter for the cone crushing operation.

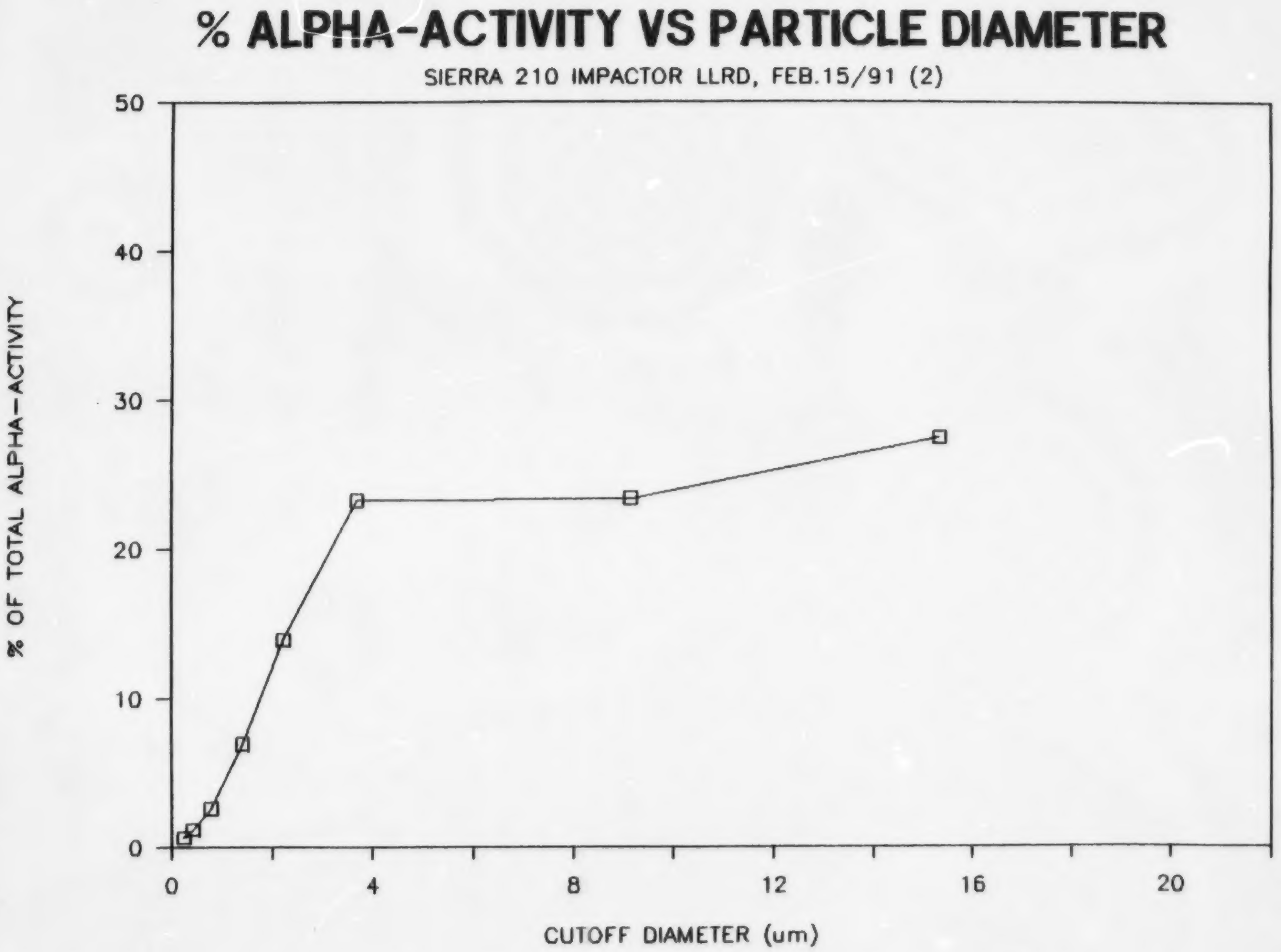


Fig. 58 - Percentage total α-particle activity versus particle cut-off diameter for the yellowcake precipitation operation.

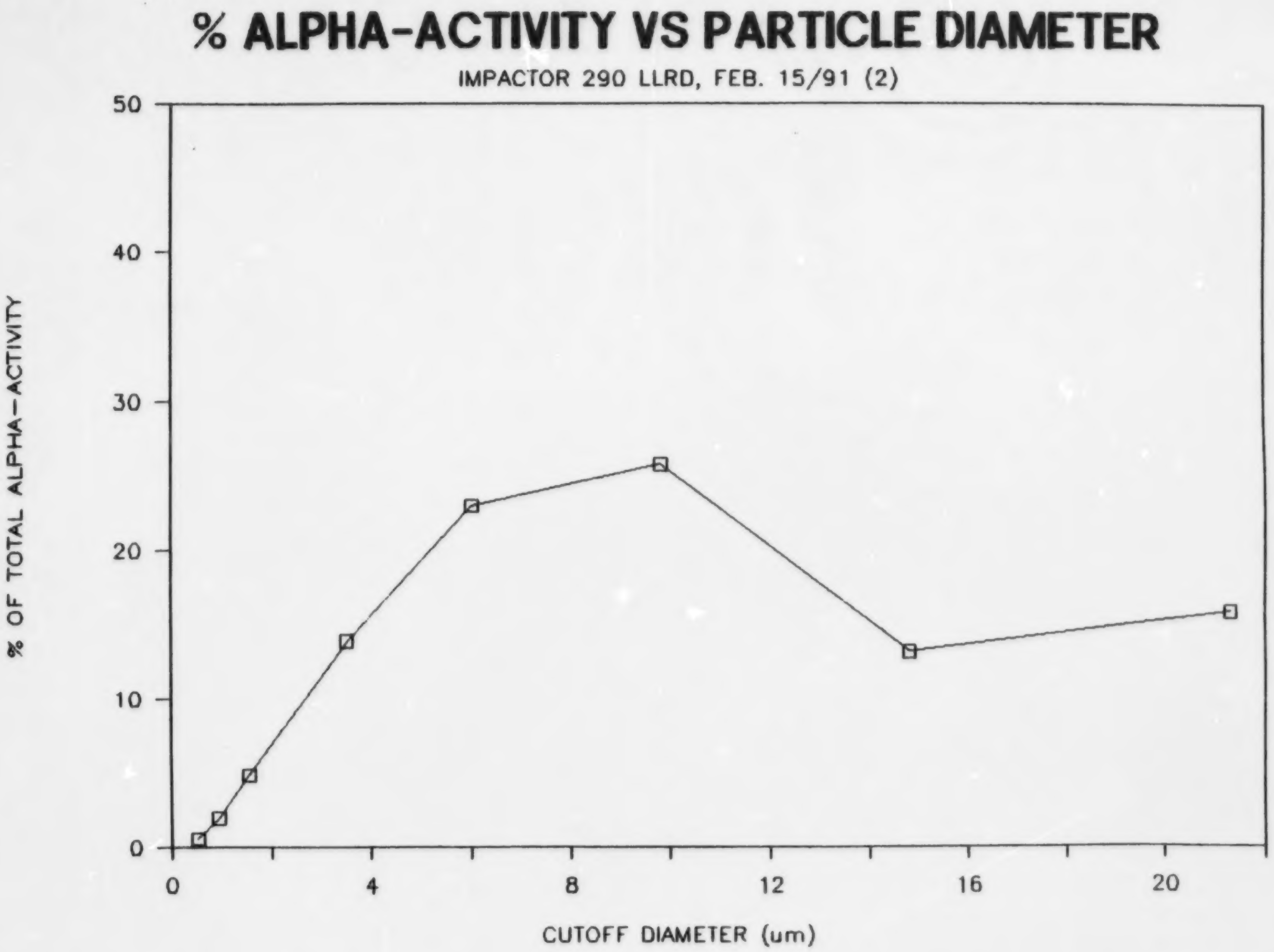


Fig. 59 - Percentage total α-particle activity versus particle cut-off diameter for the yellowcake precipitation operation.

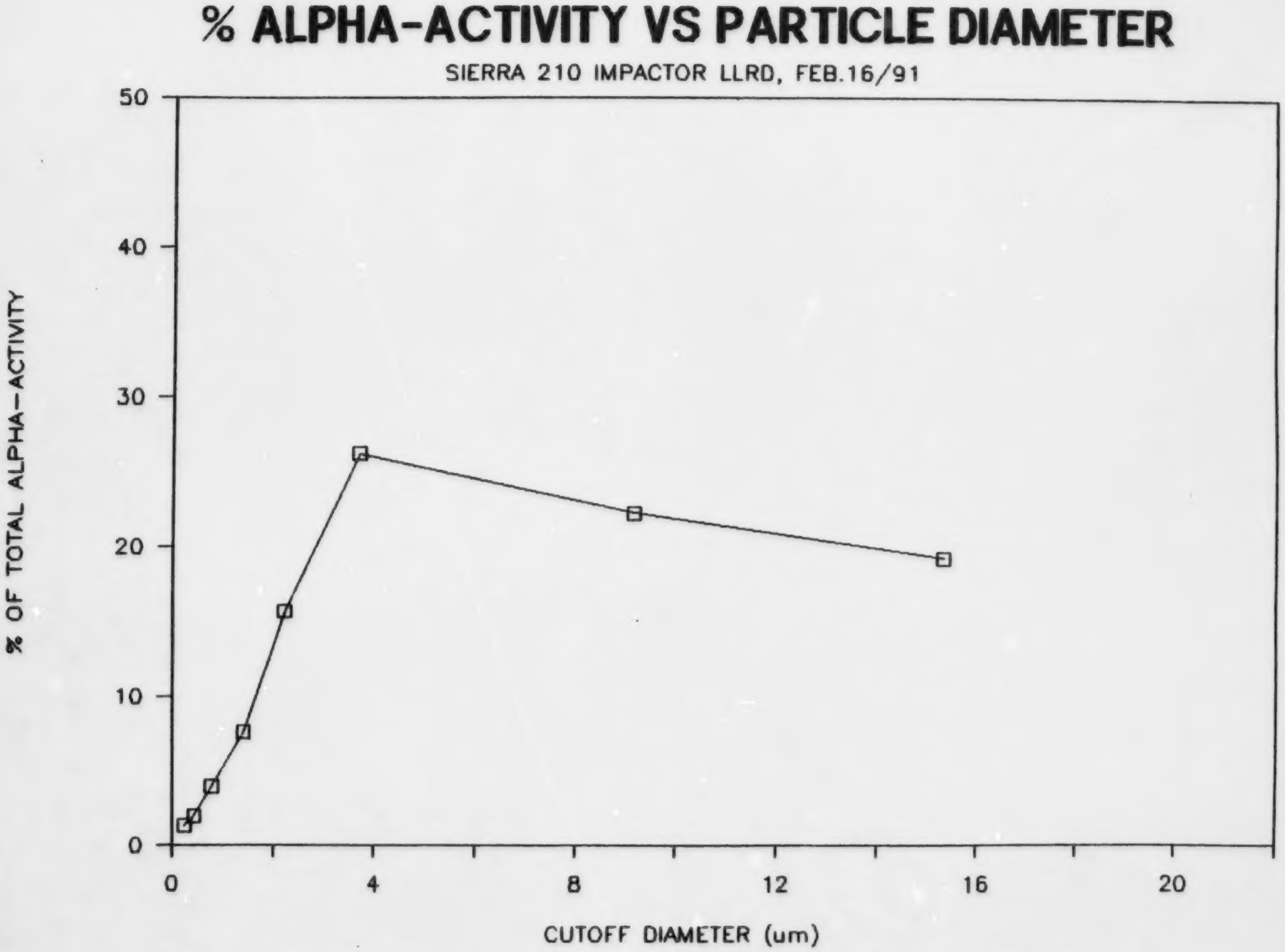


Fig. 60 - Percentage total α-particle activity versus particle cut-off diameter at the hopper/conveyor belt/ball mill area.

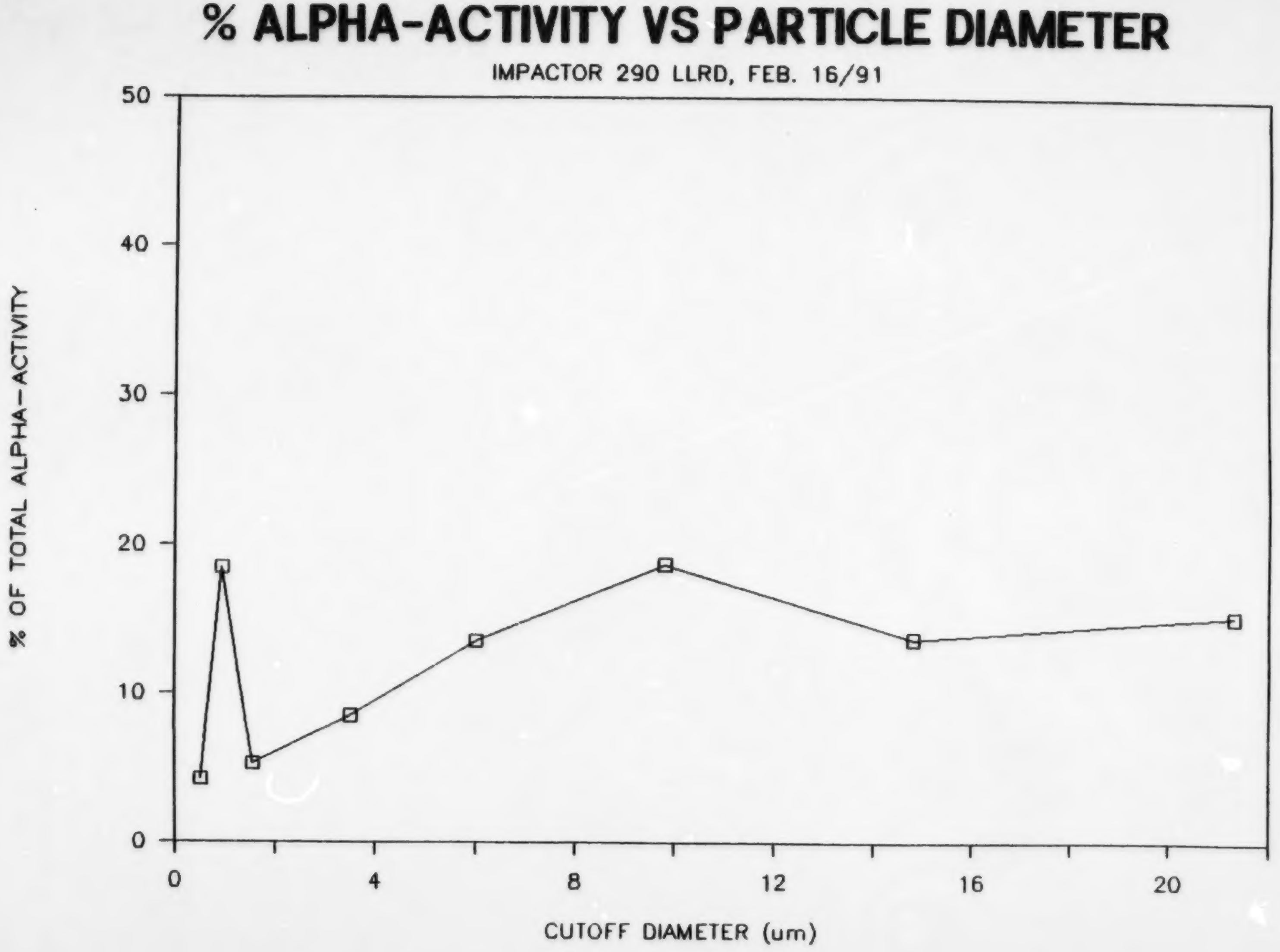


Fig. 61 - Percentage total α-particle activity versus particle cut-off diameter at the hopper/conveyor belt/ball mill area.

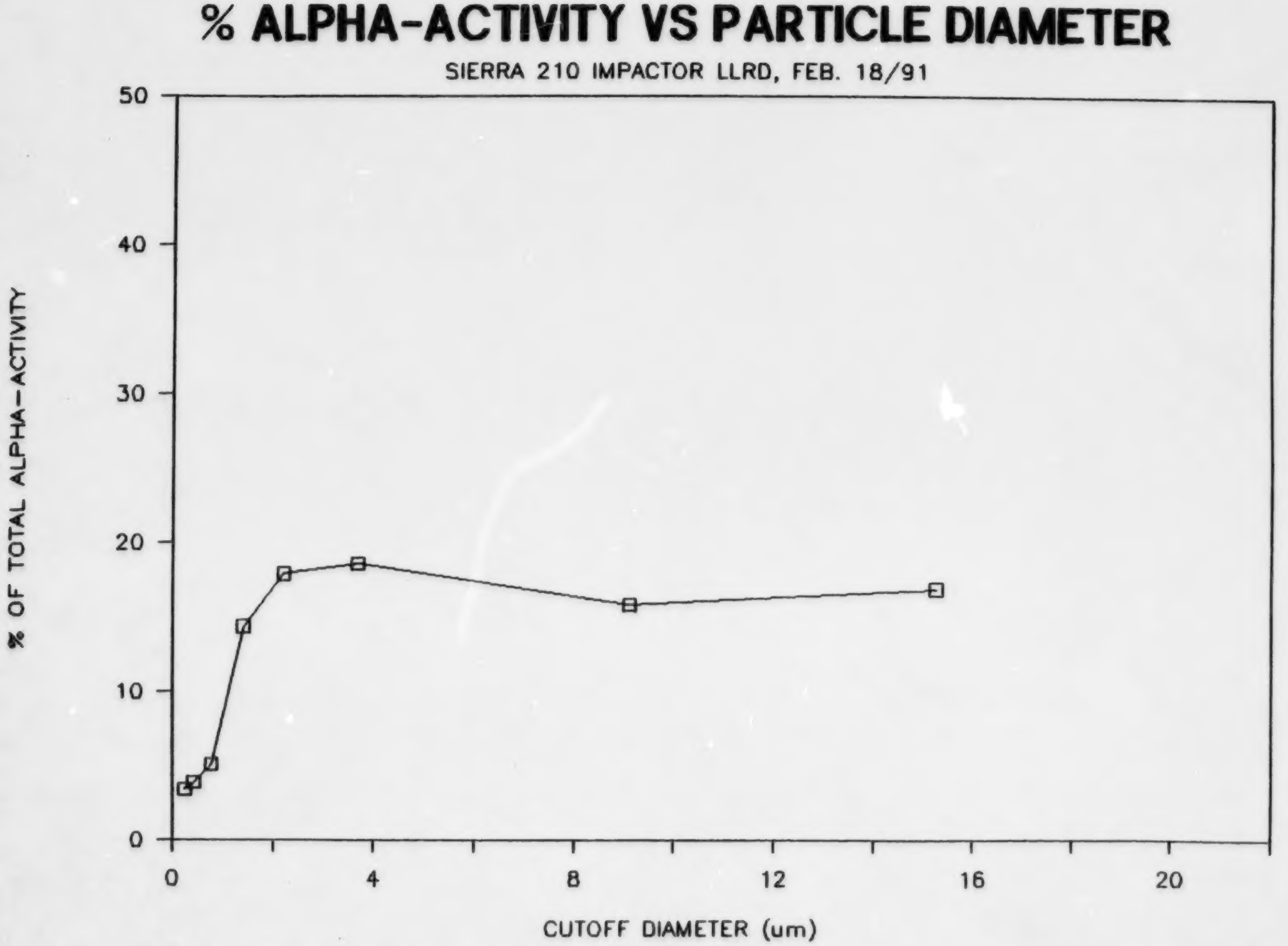


Fig. 62 - Percentage total α-particle activity versus particle cut-off diameter for the S.A.G. milling operation.

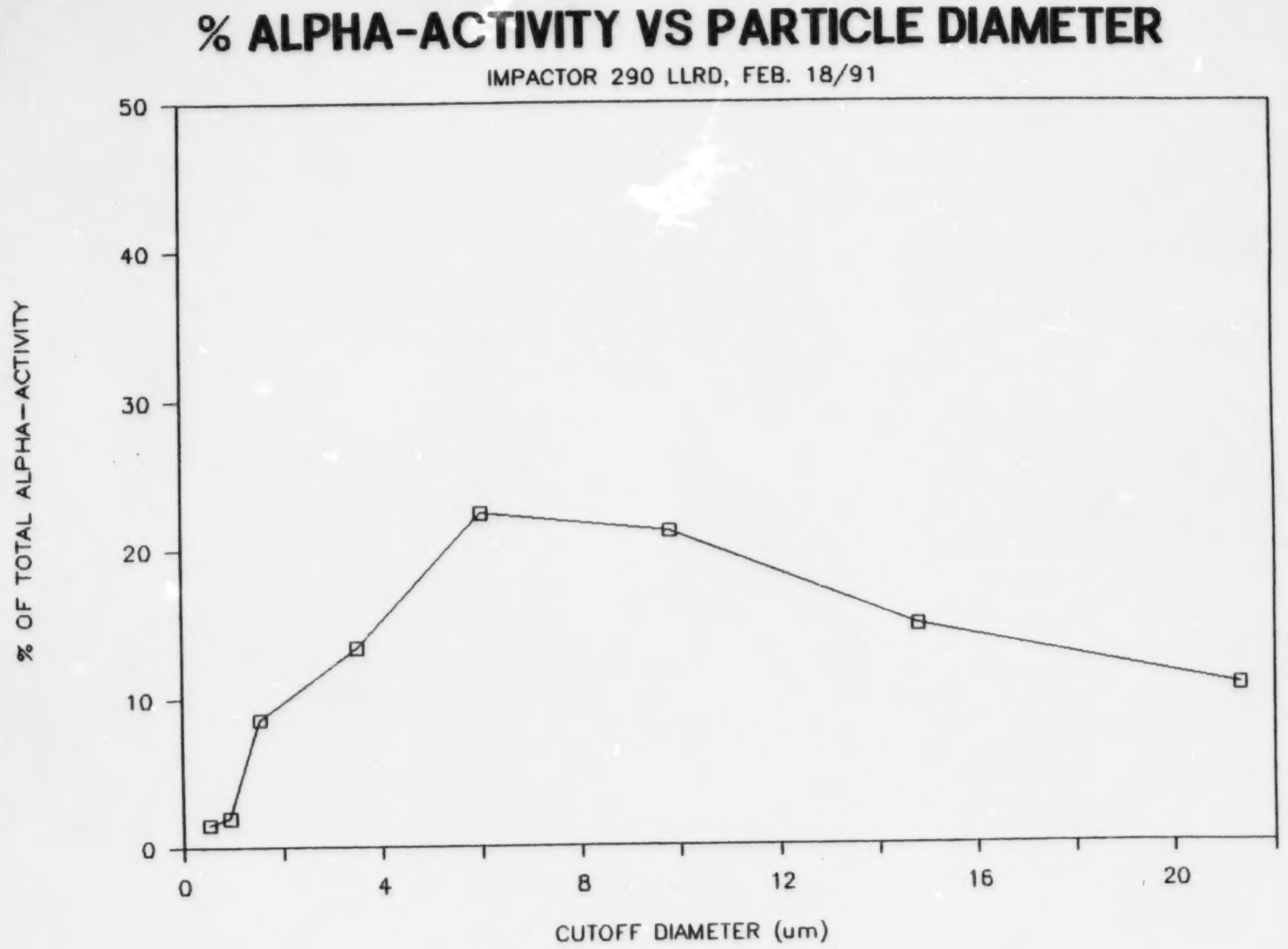


Fig. 63 - Percentage total α-particle activity versus particle cut-off diameter for the S.A.G. milling operation.

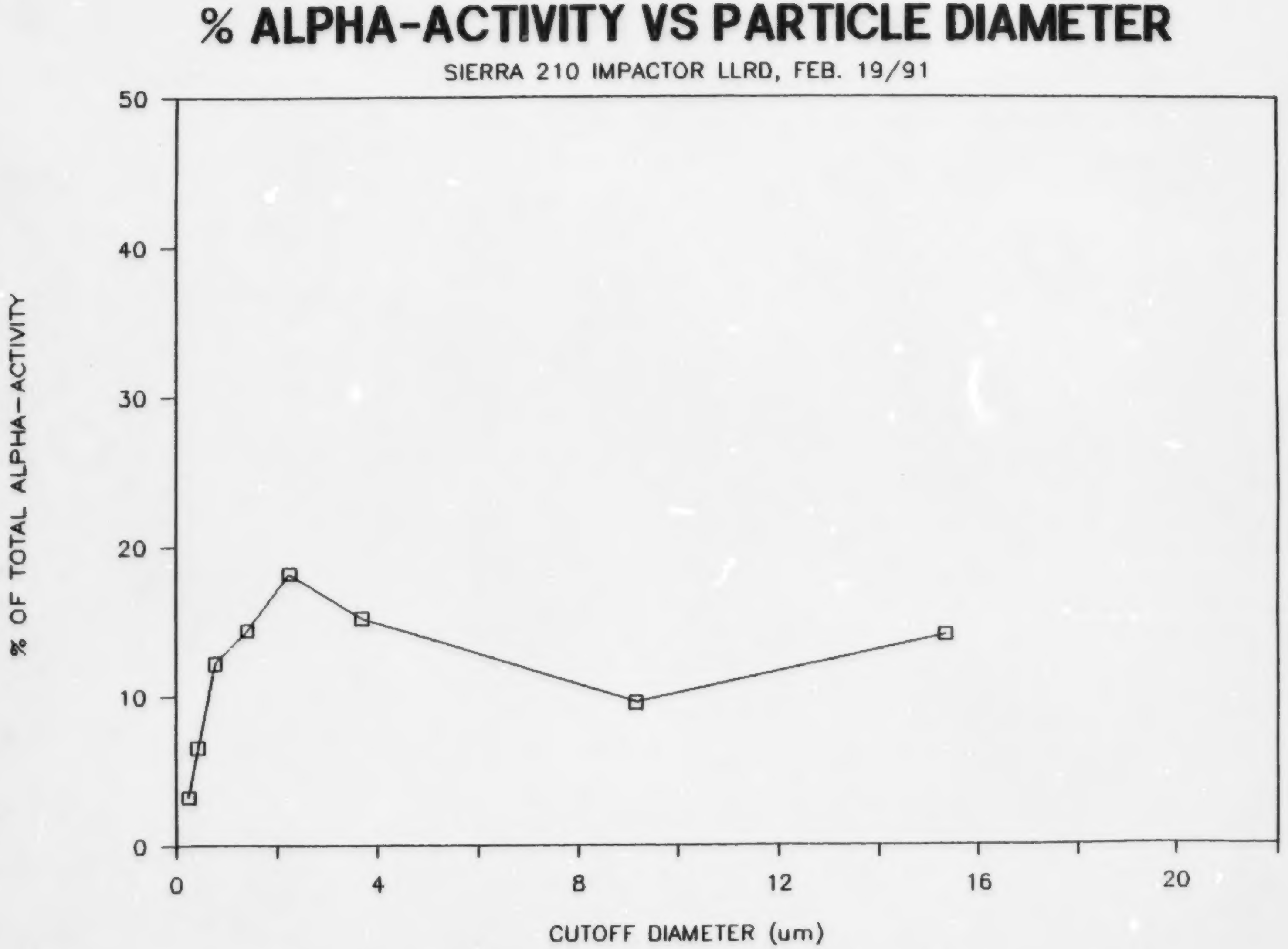


Fig. 64 - Percentage total α-particle activity versus particle cut-off diameter for the lime slaking operation.

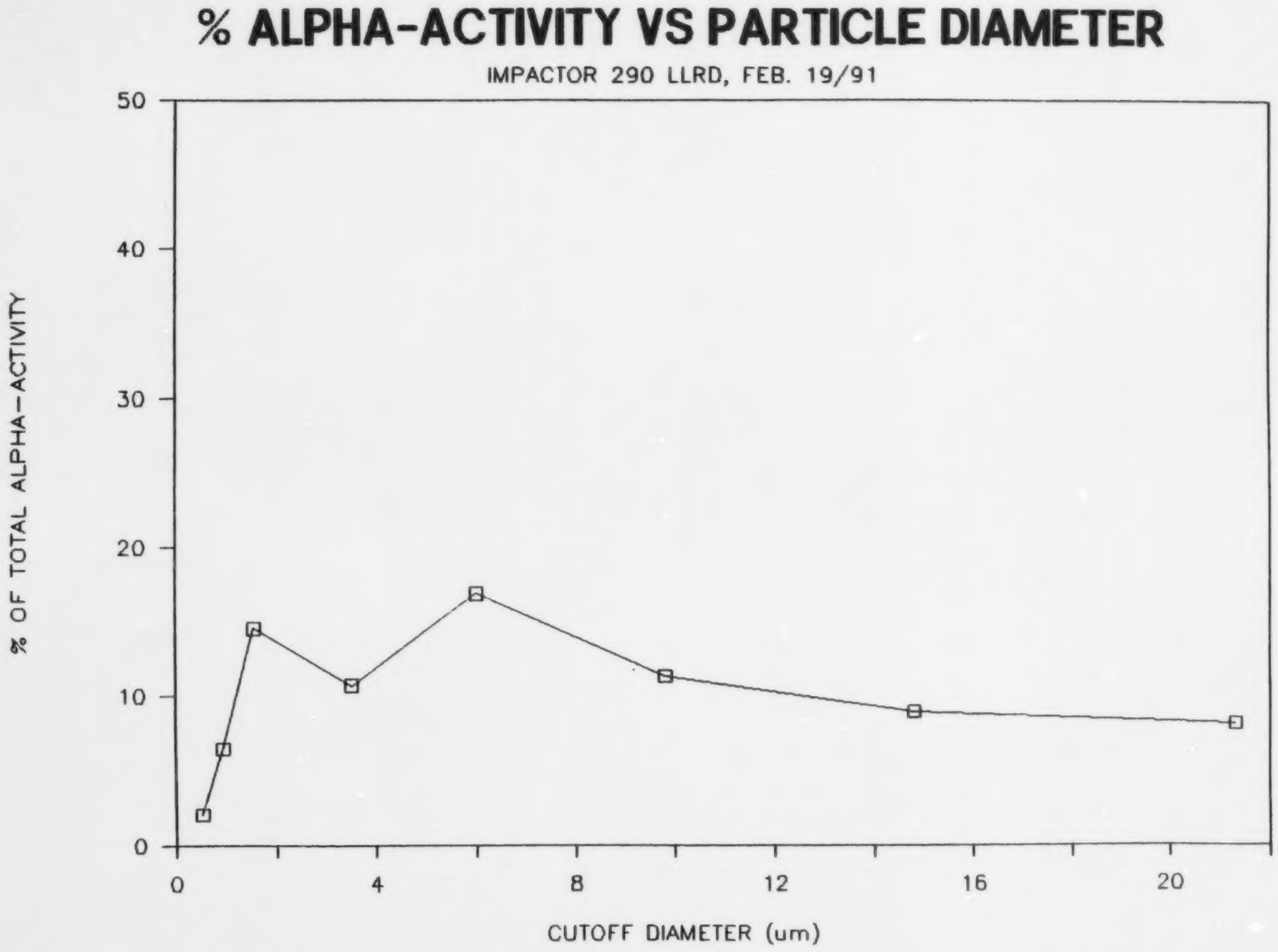


Fig. 65 - Percentage total α-particle activity versus particle cut-off diameter for the lime slaking operation.

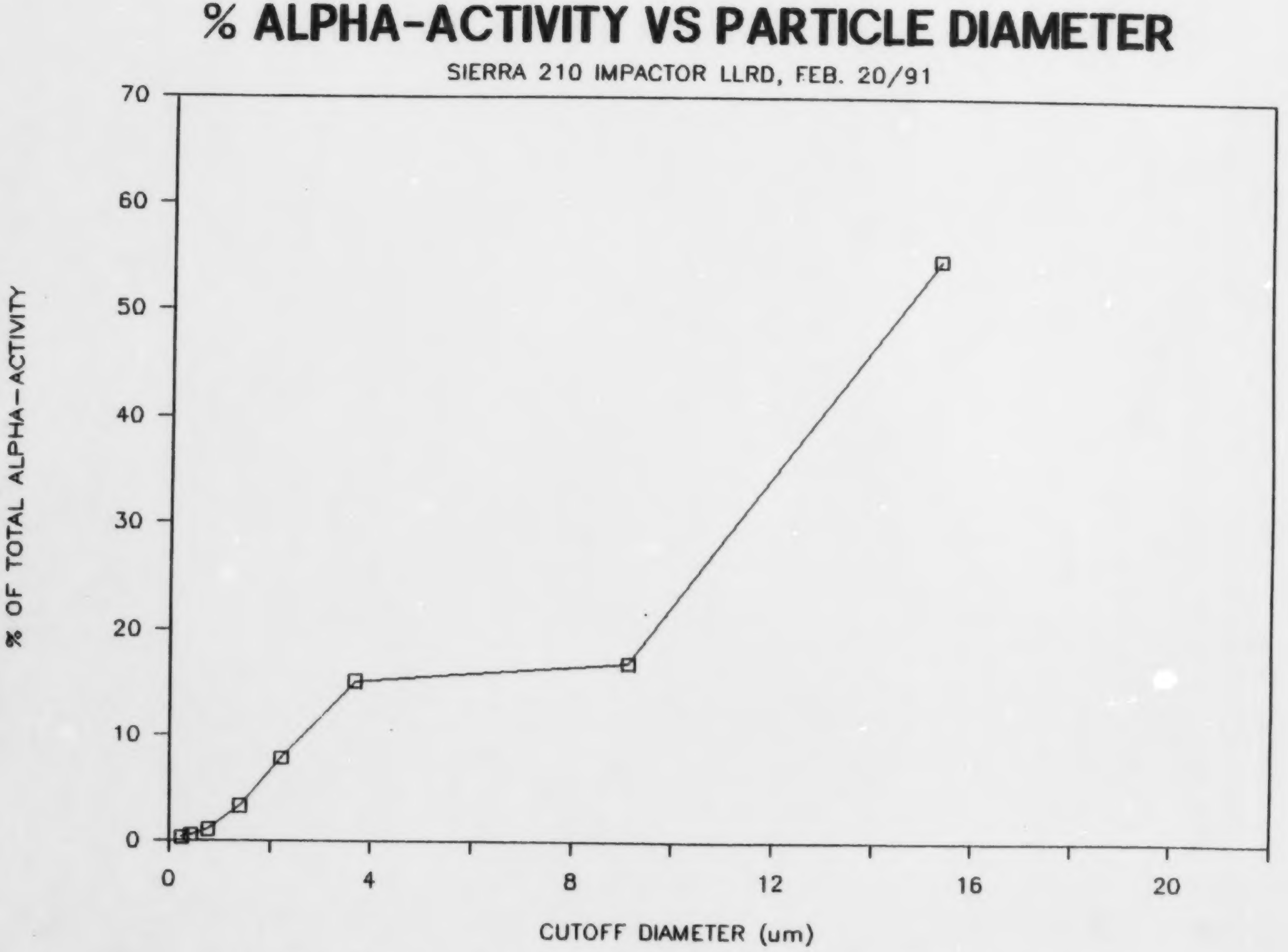


Fig. 66 - Percentage total α-particle activity versus particle cut-off diameter for the yellowcake packaging operation.

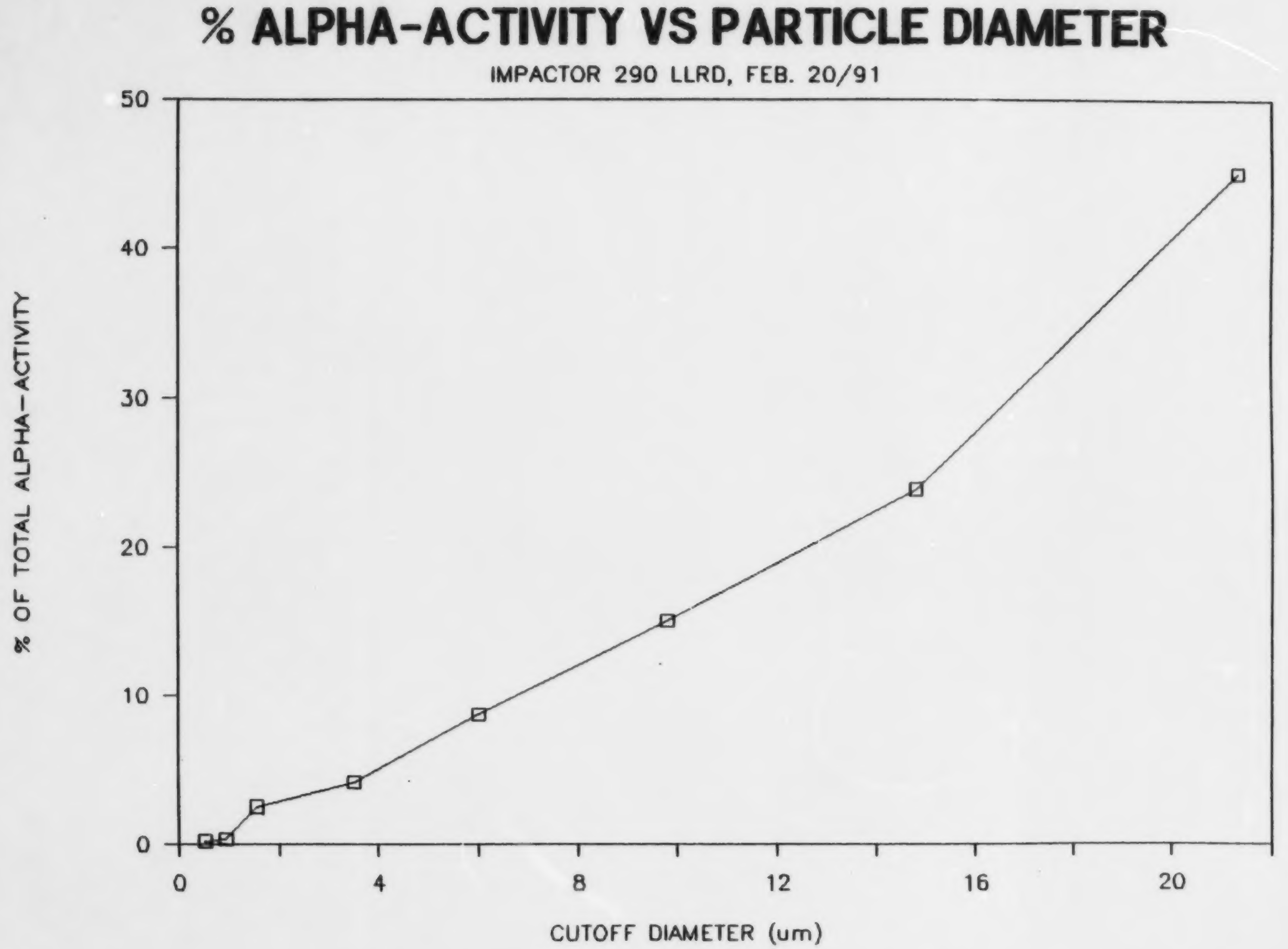
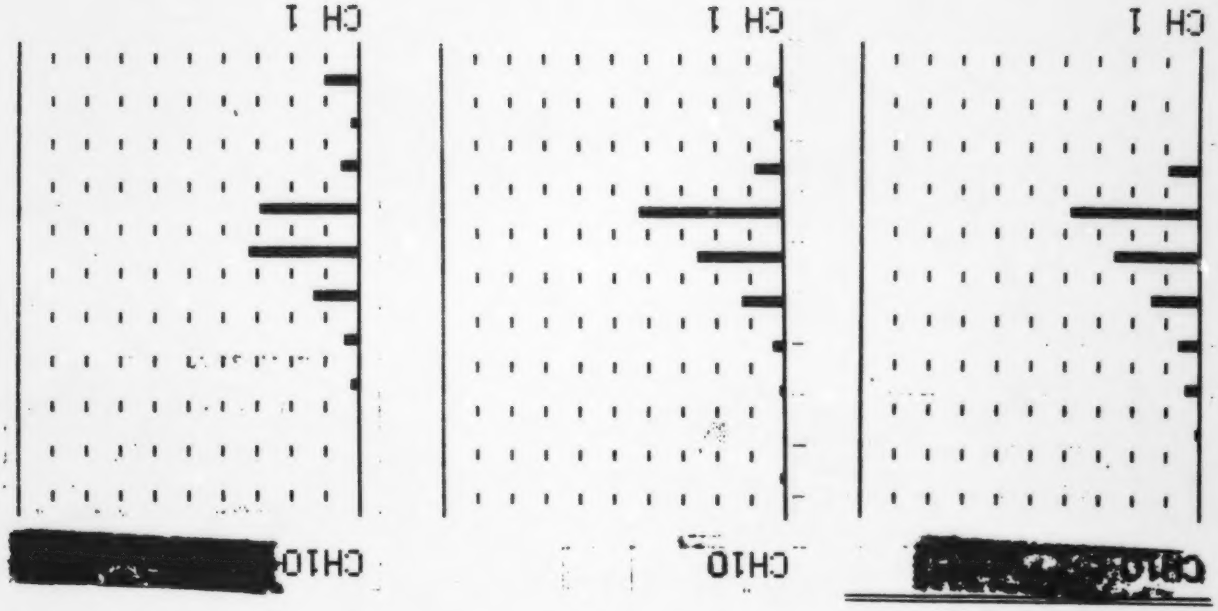
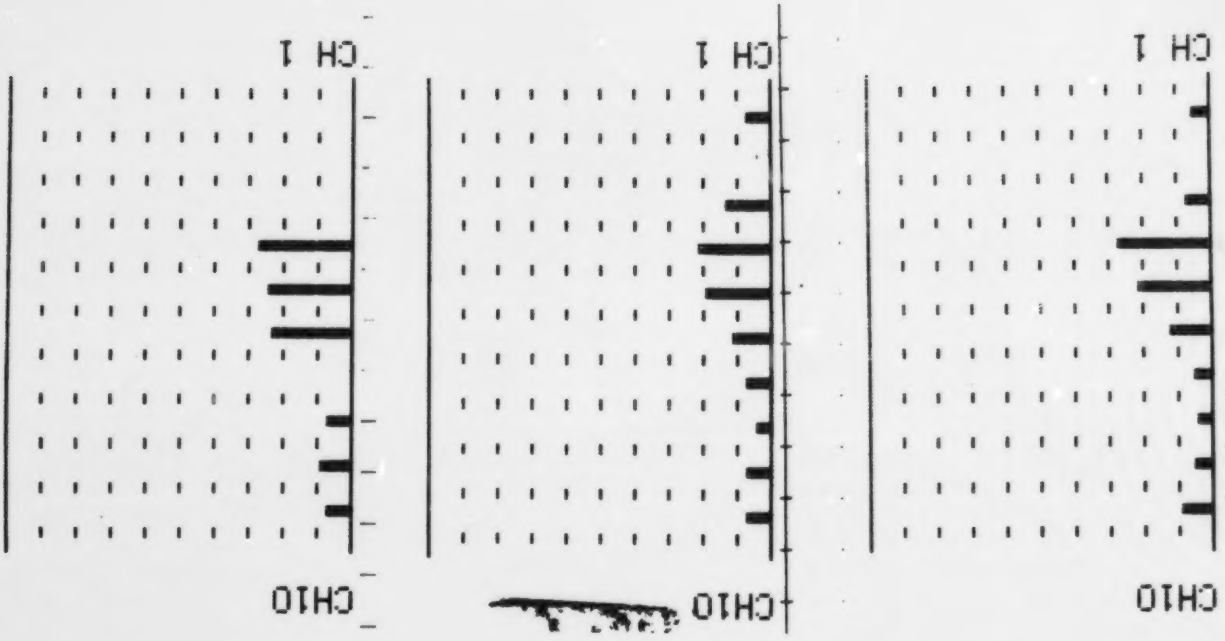


Fig. 67 - Percentage total α-particle activity versus particle cut-off diameter for the yellowcake packaging operation.



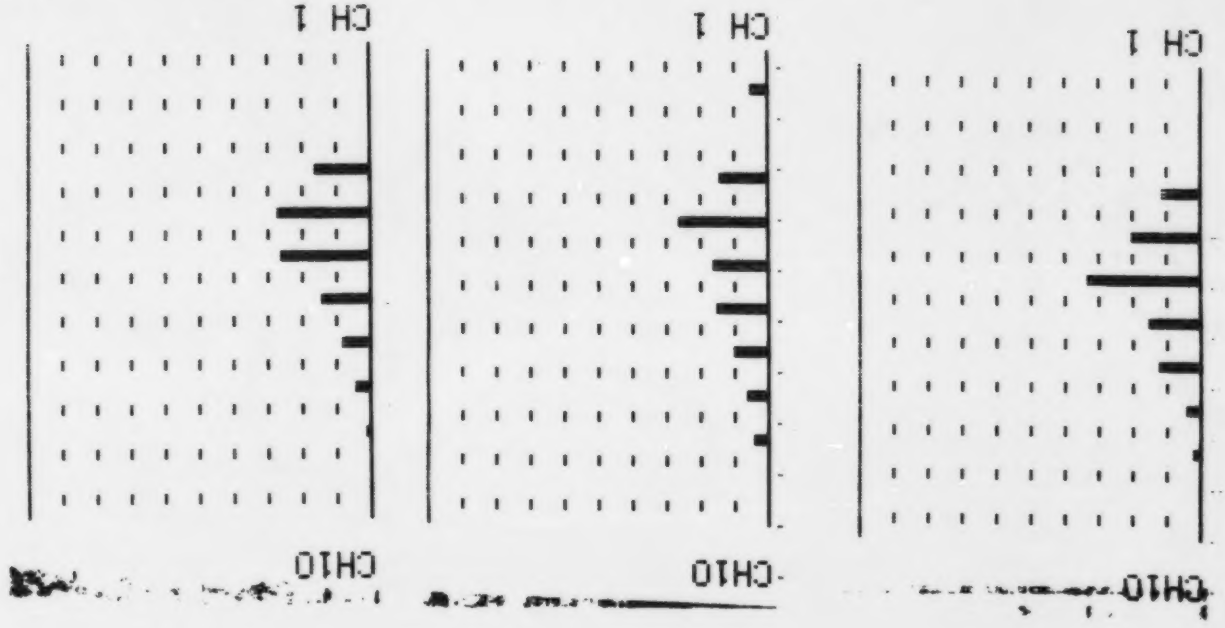
```
△T=010                    △T=010                    .△T=020

TOTAL       1.35900       TOTAL       1.60500       TOTAL       0.75300

CH   △F      mg/m³        CH   △F      mg/m³        CH   △F      mg/m³
 1 0003     0.13860        1 0001     0.04620        1 0000     0.00000
 2 0001     0.03420        2 0001     0.03420        2 0000     0.00000
 3 0002     0.06840        3 0004     0.13680        3 0004     0.06840
 4 0018     0.39960        4 0031     0.68820        4 0026     0.28860
 5 0023     0.44160        5 0021     0.40320        5 0020     0.19200
 6 0010     0.18600        6 0011     0.20460        6 0012     0.11160
 7 0003     0.05580        7 0003     0.05580        7 0005     0.04650
 8 0002     0.03480        8 0001     0.01740        8 0004     0.03480
 9 0000     0.00000        9 0000     0.00000        9 0001     0.01110
10-0001-    0.01860       10 0001     0.01860       10 0000     0.00000
```

Fig. 68 - QCM PC-2 data taken at the crusher/conveyor belt transfer point.



```
ΔT=030                       ΔT=120                       ΔT=240

TOTAL        0.07940         TOTAL        0.10460         TOTAL        0.14056

CH   ΔF      mg/m3           CH   ΔF      mg/m3           CH   ΔF      mg/m3
 1  0000    0.00000           1  0002    0.00770           1  0004    0.00770
 2  0000    0.00000           2  0000    0.00000           2  0000    0.00000
 3  0000    0.00000           3  0005    0.01425           3  0007    0.00997
 4  0003    0.02220           4  0012    0.02220           4  0042    0.03885
 5  0003    0.01920           5  0013    0.02080           5  0038    0.03040
 6  0003    0.01860           6  0008    0.01240           6  0023    0.01782
 7  0000    0.00000           7  0005    0.00775           7  0010    0.00775
 8  0001    0.00580           8  0003    0.00435           8  0008    0.00580
 9  0001    0.00740           9  0004    0.00740           9  0009    0.00832
10  0001    0.00620          10  0005    0.00775          10  0018    0.01395
```

Fig. 69 - QCM PC-2 data taken during the ball milling operation.

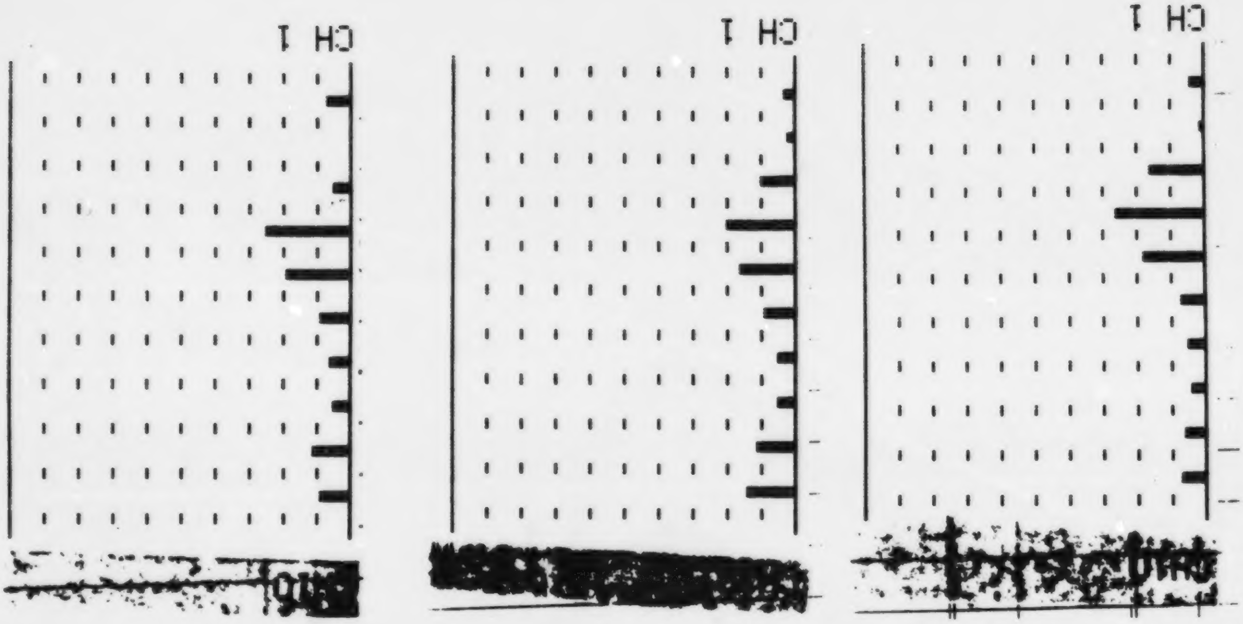


```
ΔT=030

TOTAL        0.91540

CH   ΔF        mg/m³
 1  0000     0.00000
 2  0000     0.00000
 3  0013     0.14820
 4  0034     0.25160
 5  0038     0.24320
 6  0022     0.13640
 7  0012     0.07440
 8  0007     0.04060
 9  0002     0.01480
10  0001     0.00620
```

```
ΔT=030

TOTAL        0.61240

CH   ΔF        mg/m³
 1  0002     0.03080
 2  0000     0.00000
 3  0008     0.09120
 4  0022     0.16280
 5  0016     0.10240
 6  0015     0.09300
 7  0010     0.06200
 8  0007     0.04060
 9  0004     0.02960
10  0000     0.00000
```

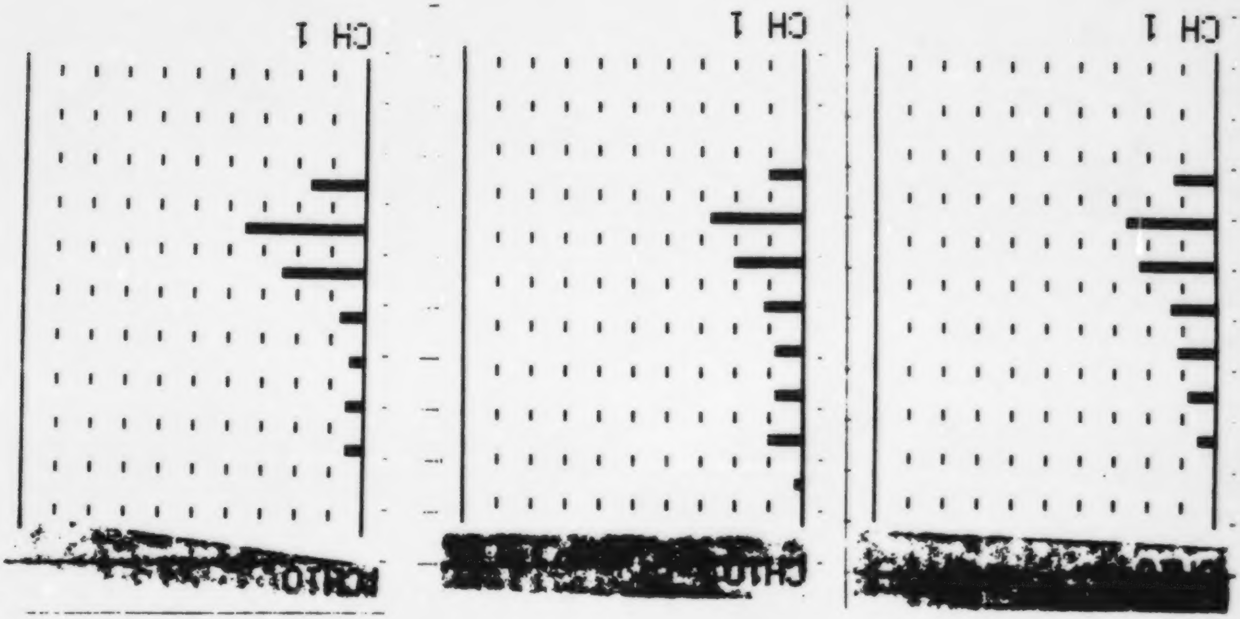
```
ΔT=030

TOTAL        0.28900

CH   ΔF        mg/m³
 1  0000     0.00000
 2  0000     0.00000
 3  0003     0.03420
 4  0008     0.05920
 5  0015     0.09600
 6  0007     0.04340
 7  0006     0.03720
 8  0002     0.01160
 9  0001     0.00740
10  0000     0.00000
```

Fig. 70 - QCM PC-2 data taken during the cone crushing operation.



```
△T=060                    △T=120                    △T=120

TOTAL      0.10020        TOTAL      0.10920        TOTAL      0.18590

CH  △F      mg/m³         CH  △F      mg/m³         CH  △F      mg/m³
 1 0001    0.00770         1 0001    0.00385         1 0002    0.00770
 2 0000    0.00000         2 0001    0.00285         2 0001    0.00285
 3 0001    0.00570         3 0004    0.01140         3 0011    0.03135
 4 0007    0.02590         4 0012    0.02220         4 0027    0.04995
 5 0006    0.01920         5 0011    0.01760         5 0022    0.03520
 6 0003    0.00930         6 0007    0.01085         6 0009    0.01395
 7 0002    0.00620         7 0004    0.00620         7 0006    0.00930
 8 0002    0.00580         8 0004    0.00580         8 0006    0.00870
 9 0003    0.01110         9 0007    0.01295         9 0007    0.01295
10 0003    0.00930        10 0010    0.01550        10 0009    0.01395
```

Fig. 71 - QCM PC-2 data taken during the yellowcake precipitation operation.

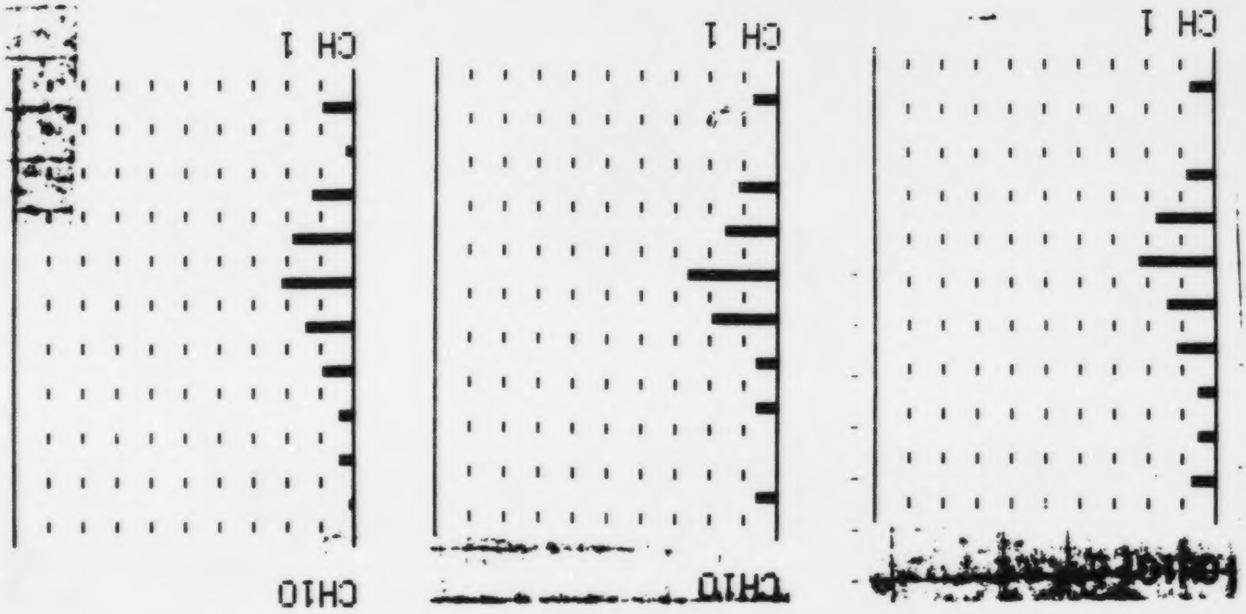


```
ΔT=090

TOTAL      0.13792

CH   ΔF      mg/m³
 1 0000    0.00000
 2 0000    0.00000
 3 0006    0.02280
 4 0020    0.04933
 5 0016    0.03413
 6 0005    0.01033
 7 0003    0.00620
 8 0004    0.00773
 9 0003    0.00740
10 0000    0.00000
```

```
ΔT=120

TOTAL      0.05400

CH   ΔF      mg/m³
 1 0000    0.00000
 2 0000    0.00000
 3 0002    0.00570
 4 0008    0.01480
 5 0007    0.01120
 6 0004    0.00620
 7 0003    0.00465
 8 0003    0.00435
 9 0003    0.00555
10 0001    0.00155
```

```
ΔT=090

TOTAL      0.09278

CH   ΔF      mg/m³
 1 0000    0.00000
 2 0000    0.00000
 3 0003    0.01140
 4 0010    0.02466
 5 0010    0.02133
 6 0006    0.01240
 7 0005    0.01033
 8 0004    0.00773
 9 0002    0.00493
10-0001-   0.00206
```

Fig. 72 - QCM PC-2 data taken at the hopper/conveyor belt/ball mill area.

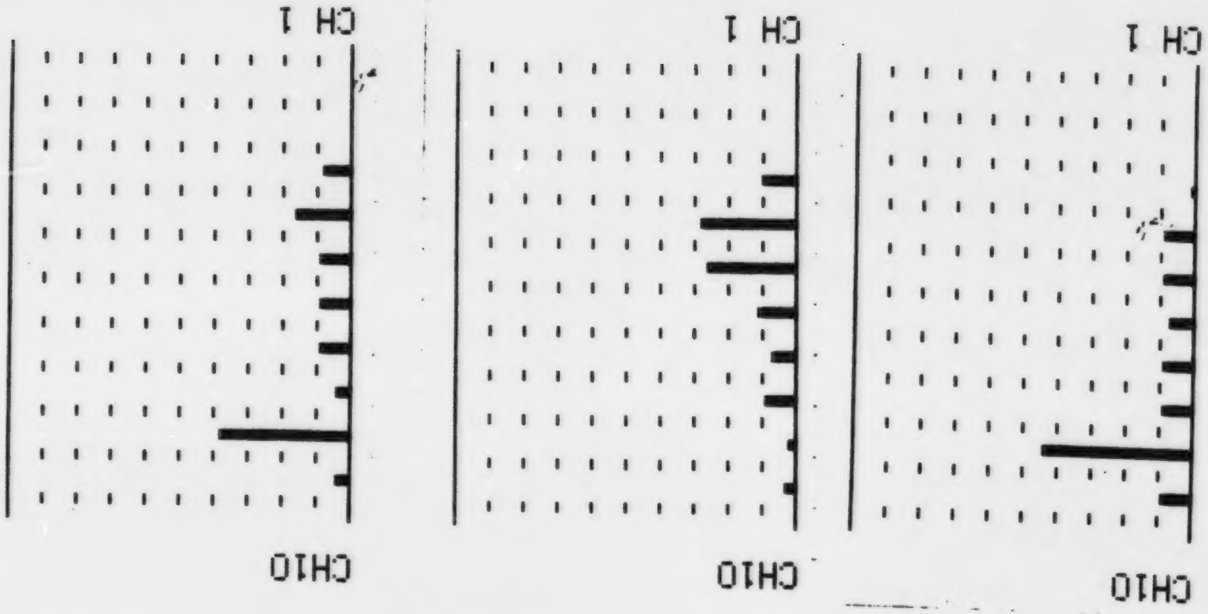


```
ΔT=900

TOTAL       0.01561

CH  ΔF      mg/m³
 1 0003     0.00154
 2 0001     0.00038
 3 0005     0.00190
 4 0012     0.00296
 5 0016     0.00341
 6 0011     0.00227
 7 0007     0.00144
 8 0004     0.00077
 9 0003     0.00074
10 0001     0.00020
```

```
ΔT=300

TOTAL       0.01926

CH  ΔF      mg/m³
 1 0001     0.00154
 2 0000     0.00000
 3 0002     0.00228
 4 0004     0.00296
 5 0008     0.00512
 6 0006     0.00372
 7 0002     0.00124
 8 0002     0.00116
 9 0000     0.00000
10 0002     0.00124
```

```
ΔT=600

TOTAL       0.02115

CH  ΔF      mg/m³
 1 0002     0.00154
 2 0000     0.00000
 3 0003     0.00171
 4 0010     0.00370
 5 0015     0.00480
 6 0010     0.00310
 7 0008     0.00248
 8 0004     0.00116
 9 0003     0.00111
10 0005     0.00155
```

Fig. 73 - QCM PC-2 data taken during the crushing operation.

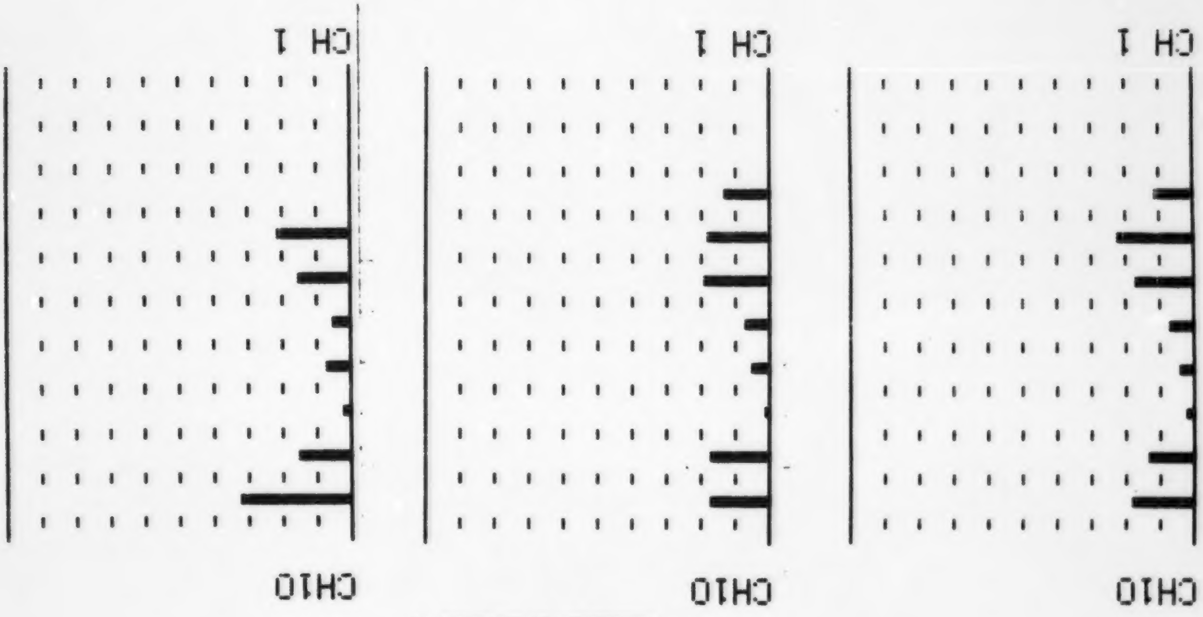


```
ΔT=060

TOTAL        0.06750

CH  ΔF       mg/m³
 1-0001-     0.00770
 2 0000      0.00000
 3 0001      0.00570
 4 0003      0.01110
 5 0002      0.00640
 6 0002      0.00620
 7 0002      0.00620
 8 0001      0.00290
 9 0007      0.02590
10 0001      0.00310
```

```
ΔT=180

TOTAL        0.05281

CH  ΔF       mg/m³
 1 0000      0.00000
 2 0000      0.00000
 3 0003      0.00570
 4 0012      0.01480
 5 0013      0.01386
 6 0006      0.00620
 7 0004      0.00413
 8 0005      0.00483
 9 0001      0.00123
10 0002      0.00206
```

```
ΔT=360

TOTAL        0.07258

CH  ΔF       mg/m³
 1-0003-     0.00385
 2-0001-     0.00095
 3 0001      0.00095
 4 0011      0.00678
 5 0013      0.00693
 6 0010      0.00516
 7 0013      0.00671
 8 0014      0.00676
 9 0052      0.03206
10 0014      0.00723
```

Fig. 74 - QCM PC-2 data taken during the lime slaking operation.

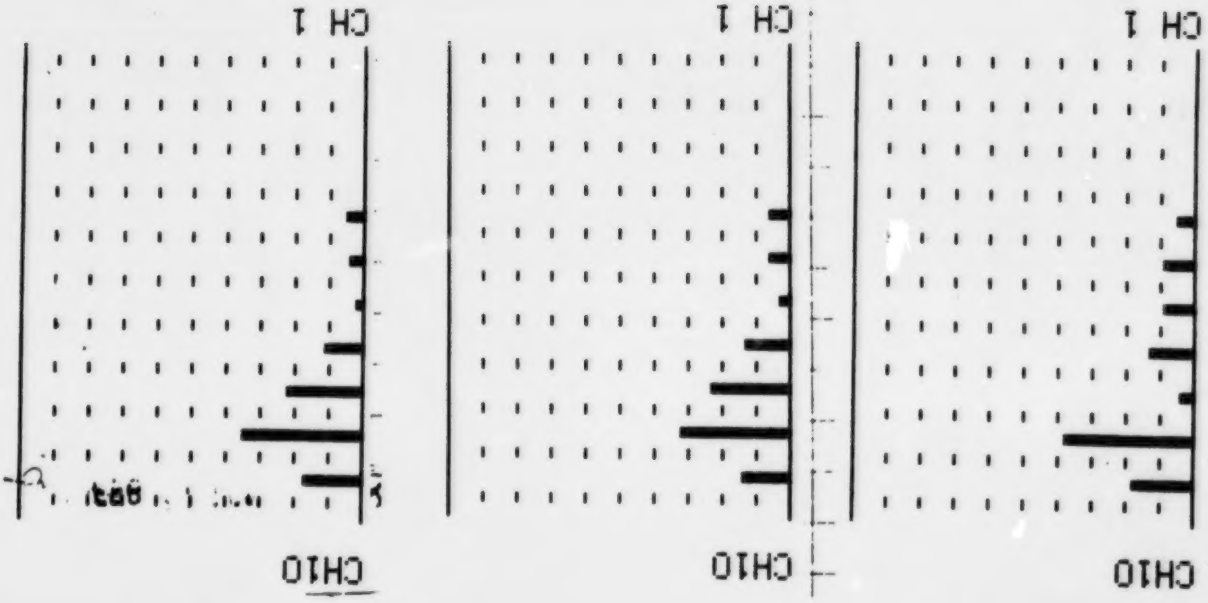


```
△T=360

TOTAL         0.02036

CH   △F       mg/m³
 1-0001-    0.00128
 2-0001-    0.00095
 3 0000     0.00000
 4 0007     0.00431
 5 0006     0.00320
 6 0002     0.00103
 7 0003     0.00155
 8 0001     0.00048
 9 0005     0.00308
10 0013     0.00671
```

```
△T=360

TOTAL         0.03594

CH   △F       mg/m³
 1-0001-    0.00128
 2 0000     0.00000
 3 0005     0.00475
 4 0011     0.00678
 5 0013     0.00693
 6 0005     0.00258
 7 0004     0.00206
 8 0001     0.00048
 9 0010     0.00616
10 0012     0.00620
```

```
△T=360

TOTAL         0.03266

CH   △F       mg/m³
 1-0001-    0.00128
 2 0000     0.00000
 3 0004     0.00380
 4 0012     0.00740
 5 0011     0.00586
 6 0005     0.00258
 7 0003     0.00155
 8 0002     0.00096
 9 0007     0.00431
10 0012     0.00620
```

Fig. 75 - QCM PC-2 data taken during the yellowcake packaging operation.



```
△T=020                    △T=030                    △T=030

TOTAL      0.83430        TOTAL      0.72360        TOTAL      0.13360

CH  △F     mg/m³          CH  △F     mg/m³          CH  △F     mg/m³
 1-0002-   0.04620         1-0002-   0.03080         1  0000   0.00000
 2 0000    0.00000         2-0001-   0.01140         2  0000   0.00000
 3-0001-   0.01710         3-0002-   0.02280         3  0000   0.00000
 4 0004    0.04440         4 0006    0.04440         4  0001   0.00740
 5 0004    0.03840         5 0007    0.04480         5  0002   0.01280
 6 0002    0.01860         6 0004    0.02480         6  0002   0.01240
 7 0010    0.09300         7 0016    0.09920         7  0003   0.01860
 8 0022    0.19140         8 0029    0.16820         8  0001   0.00580
 9 0027    0.29970         9 0032    0.23680         9  0007   0.05180
10 0016    0.14880        10 0017    0.10540        10  0004   0.02480
```

Fig. 76 - QCM PC-2 data taken at the yellowcake baghouse filter.

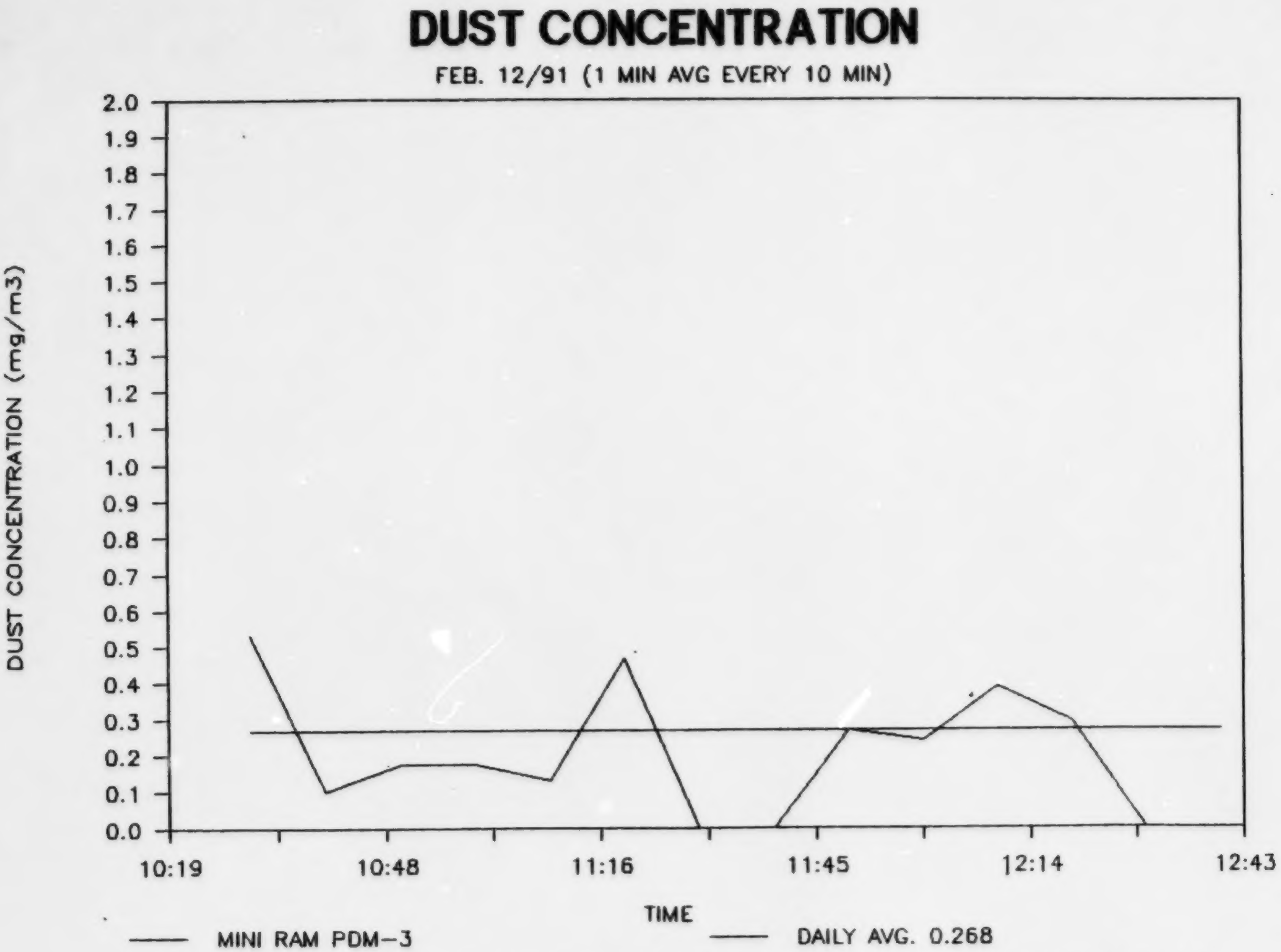


Fig. 77 - Dust concentration versus time at the crusher/conveyor belt transfer point.

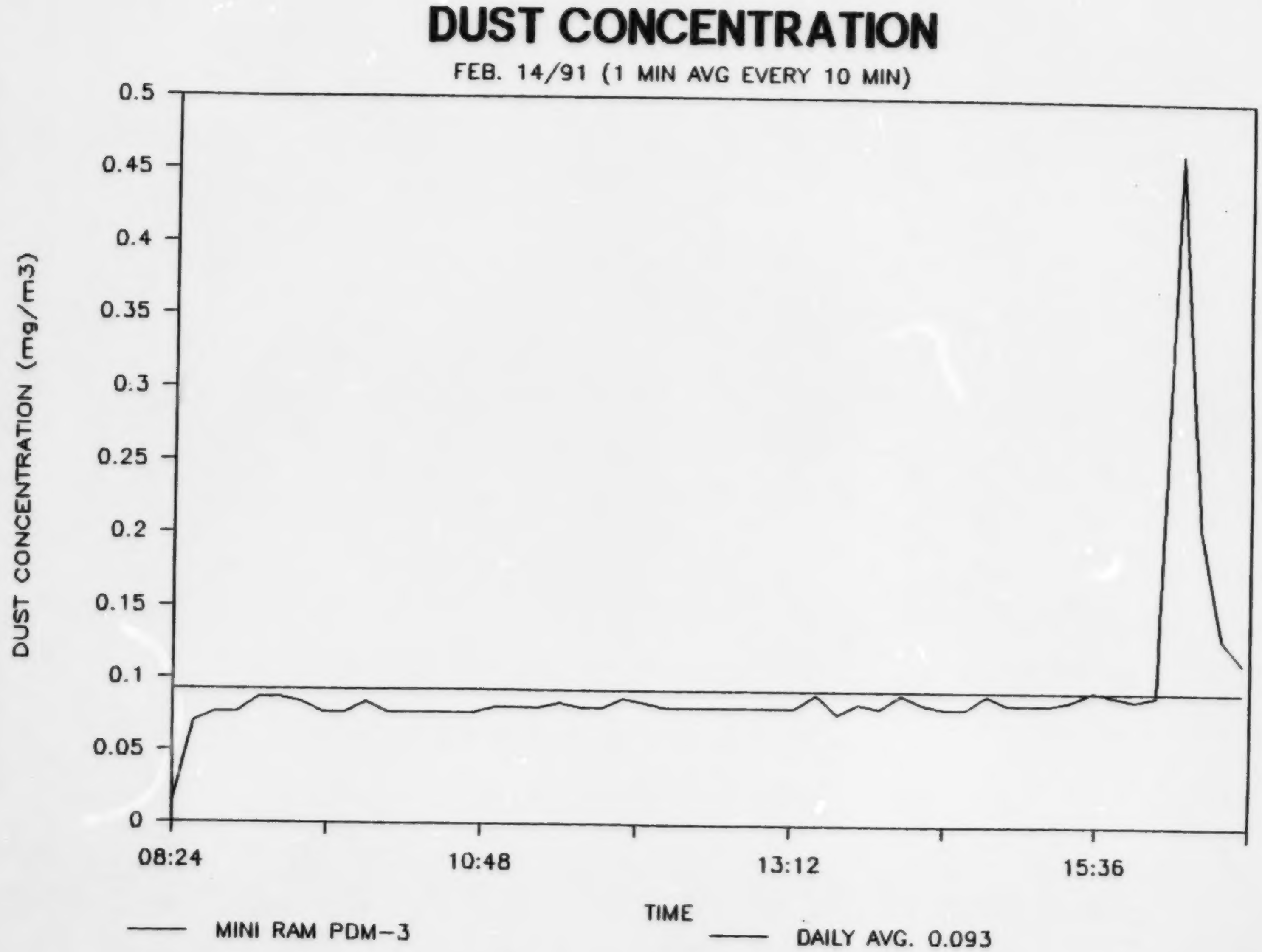


Fig. 78 - Dust concentration versus time measured during the ball milling operation.

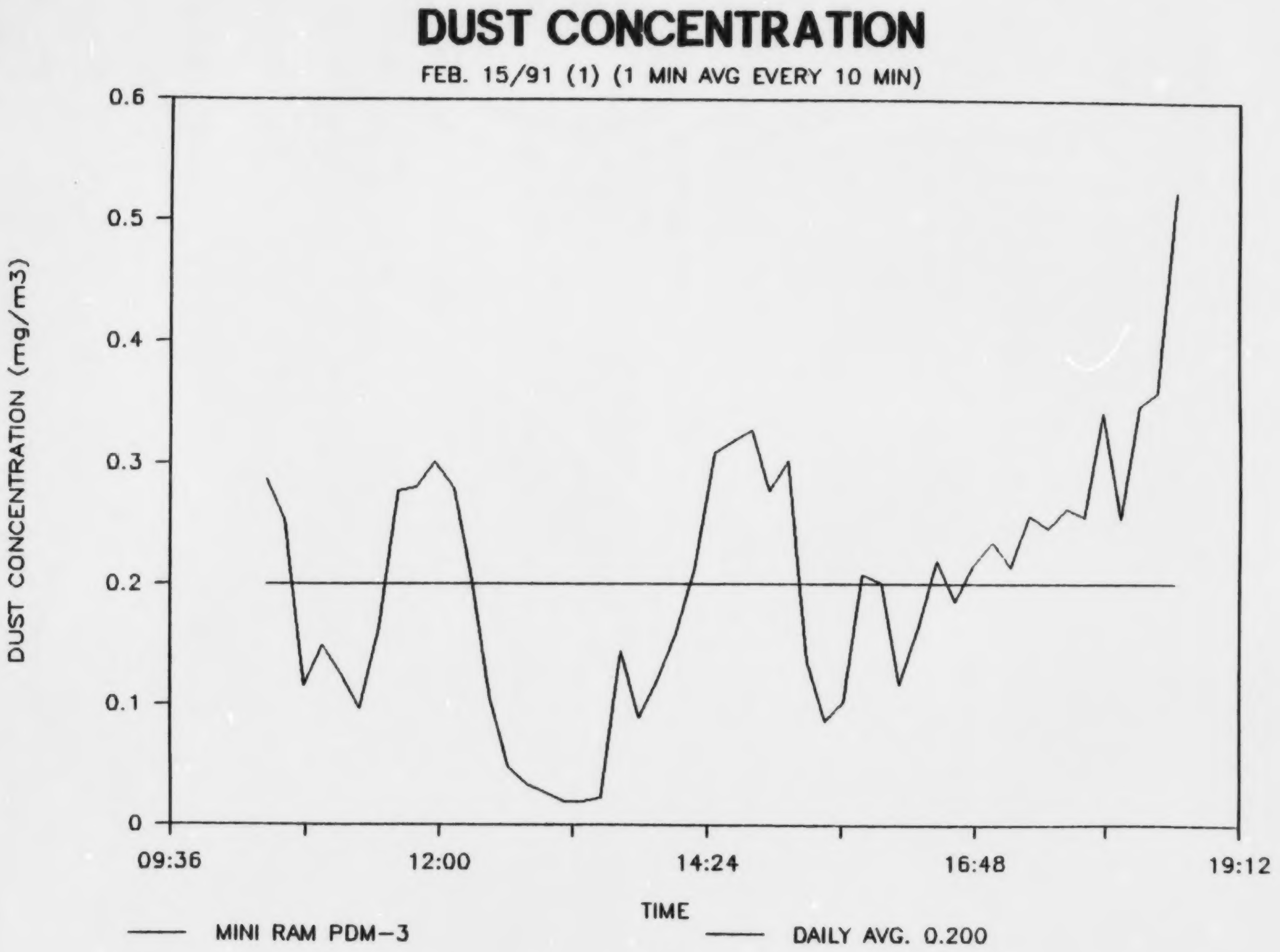


Fig. 79 - Dust concentration versus time measured during the crushing operation.

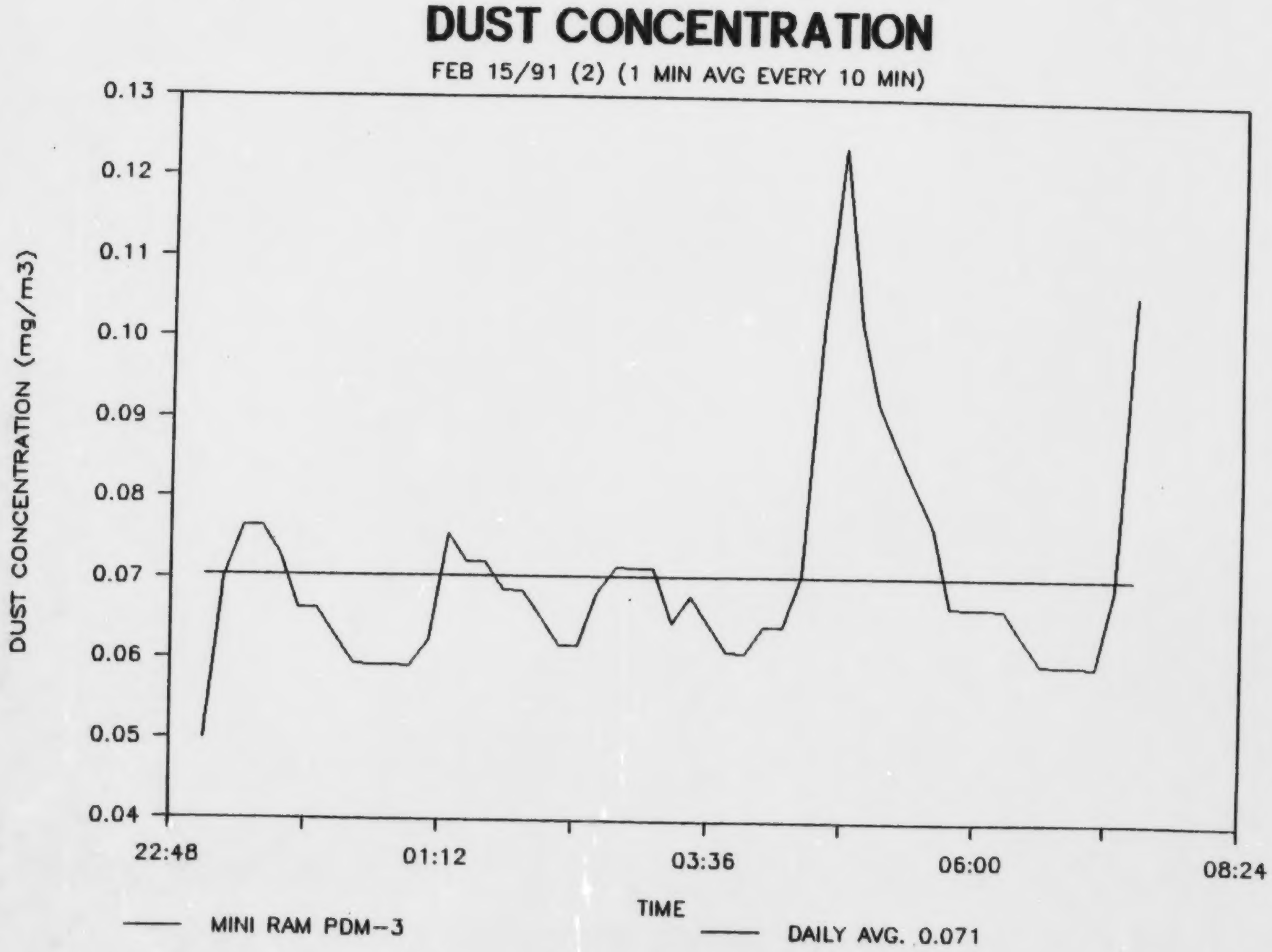


Fig. 80 - Dust concentration versus time measured during the yellowcake precipitation operation.

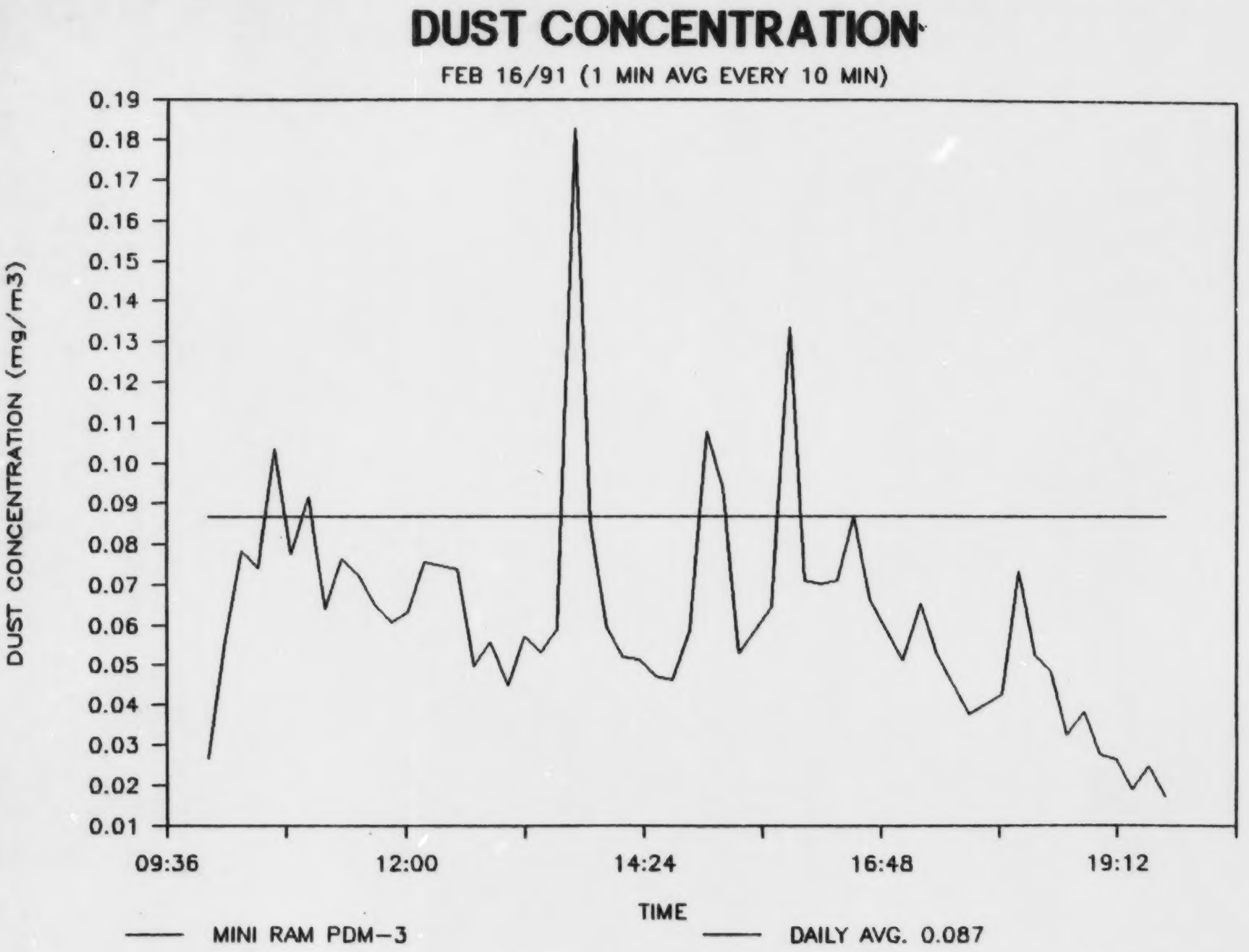


Fig. 81 - Dust concentration versus time measured at the hopper/conveyor belt/ball mill area.

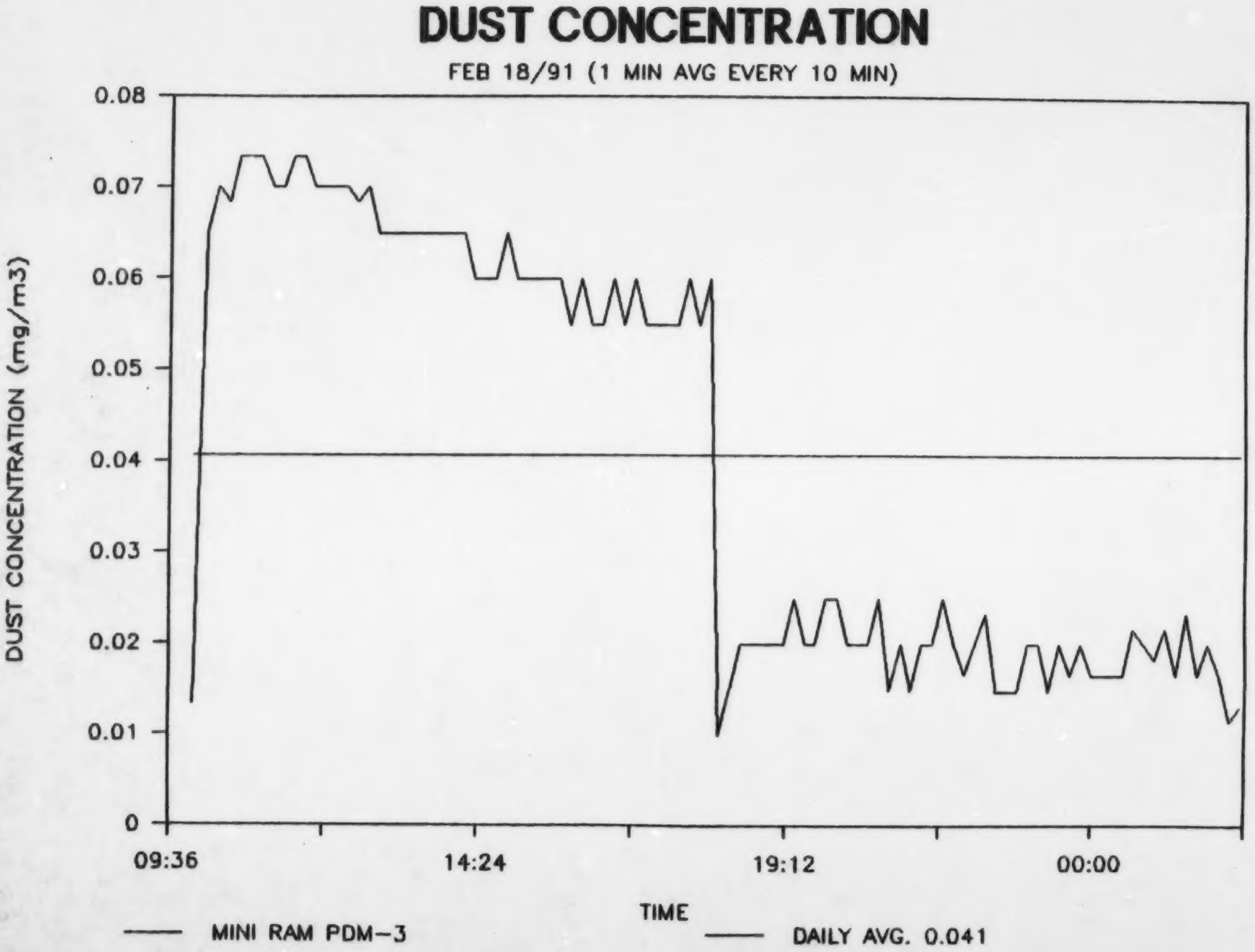


Fig. 82 - Dust concentration versus time measured during the S.A.G. milling operation.

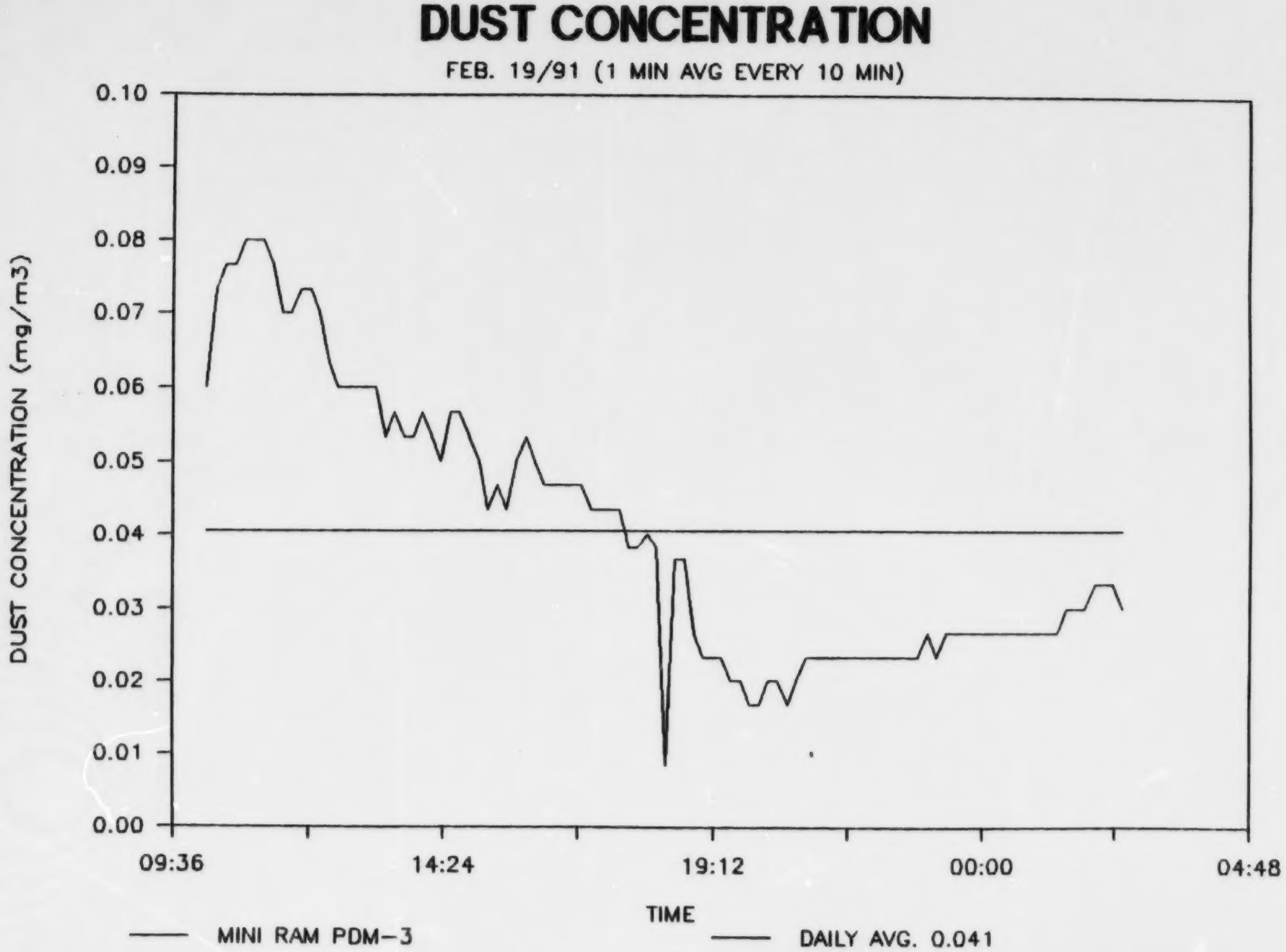


Fig. 83 - Dust concentration versus time measured during the lime slaking operation.

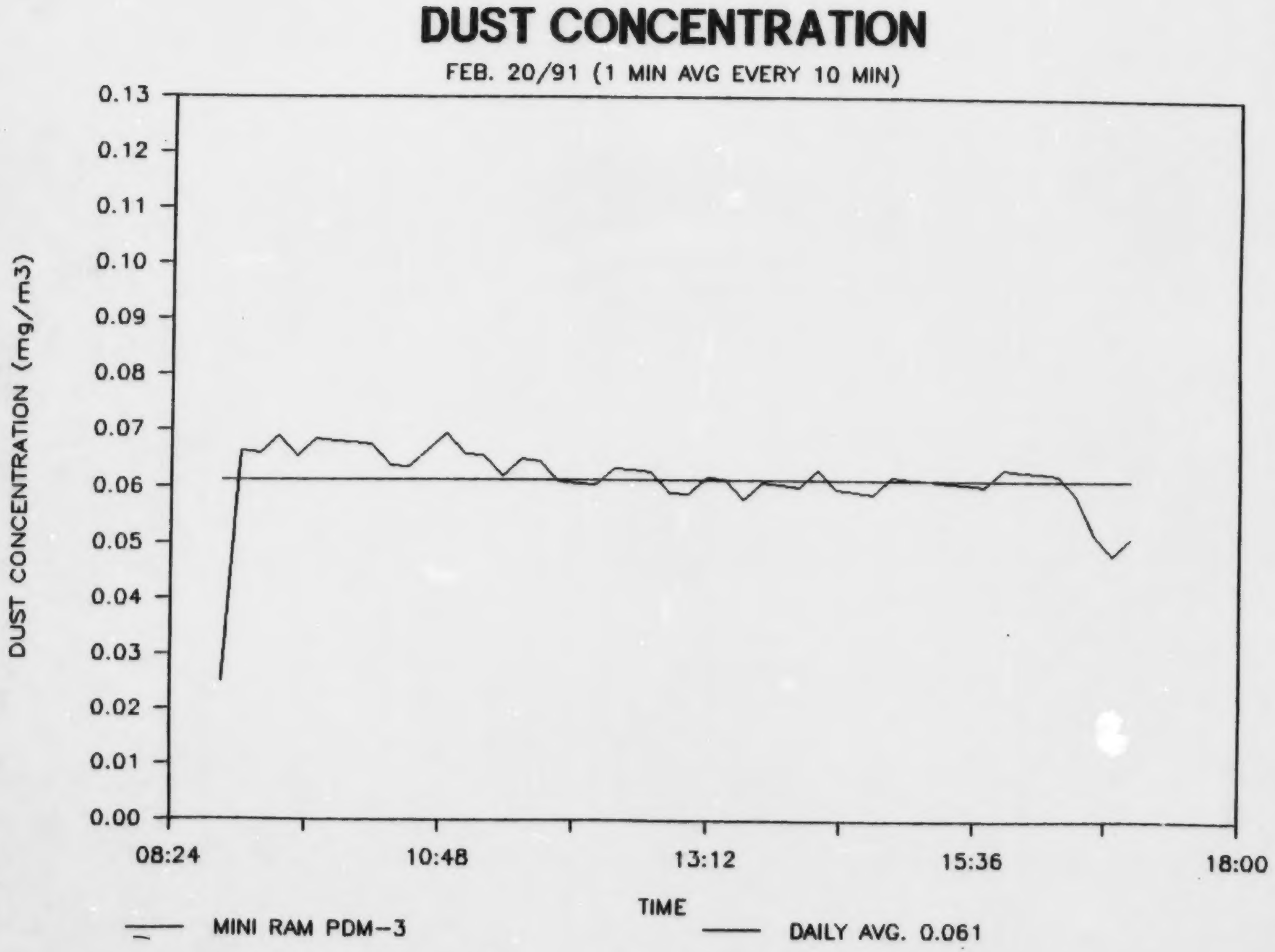


Fig. 84 - Dust concentration versus time measured during the yellowcake packaging operation.

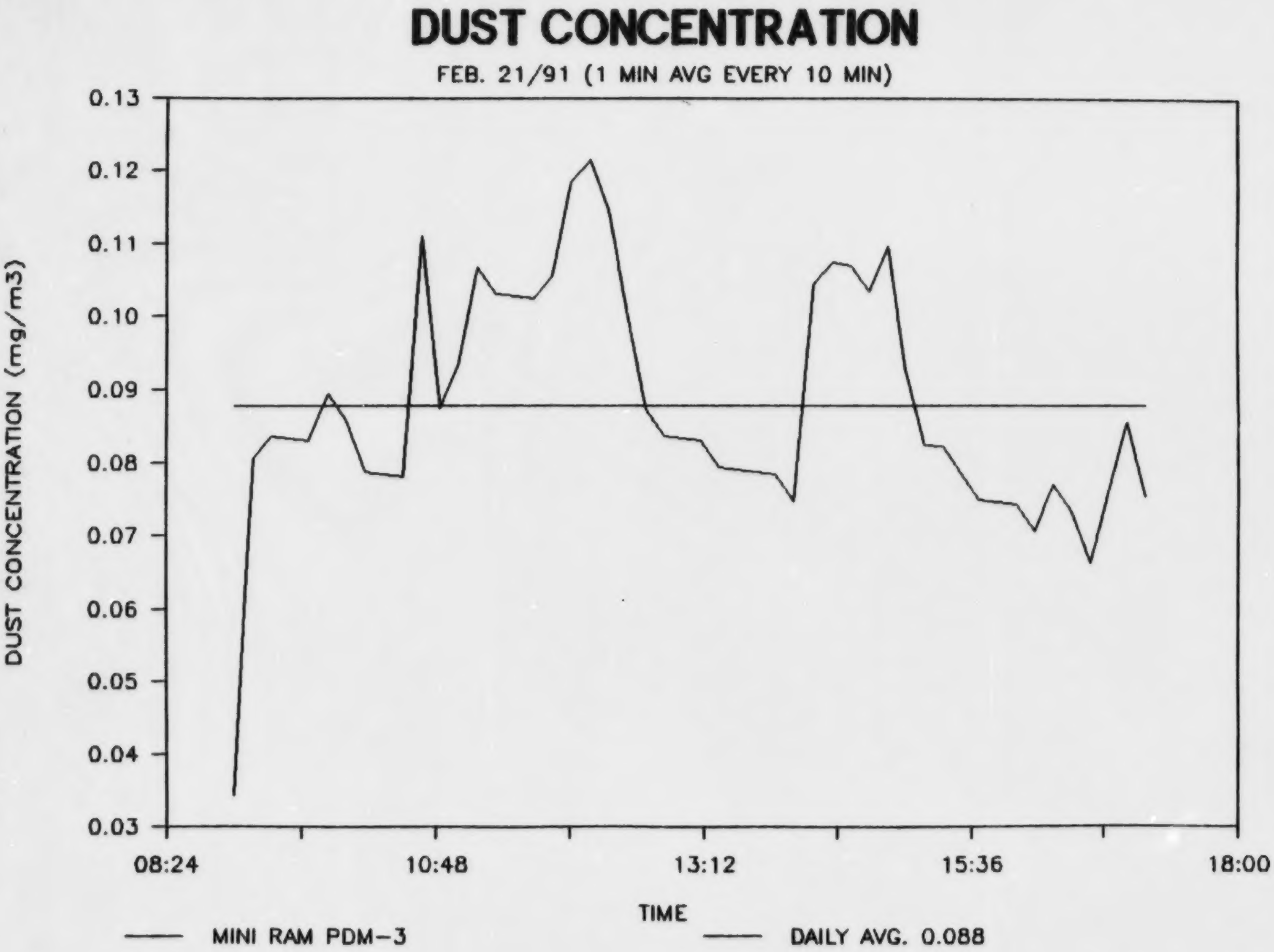


Fig. 85 - Dust concentration versus time measured during the yellowcake packaging operation.

APPENDIX A

As previously indicated in sub-section 2, entitled "Dust Mass and α-Particle Activity Versus Particle Size Distribution", Figures A-1 to A-32 show similar data to Figure 36 to 67, but presented in a different way. In the present case, the figures are presented as follows:

a) Percentage dust mass versus cut-off diameter followed by the percentage α-particle activity versus cut-off diameter, both graphs for the Sierra 210, followed by:

b) the same as item a) but for the Marple 290.

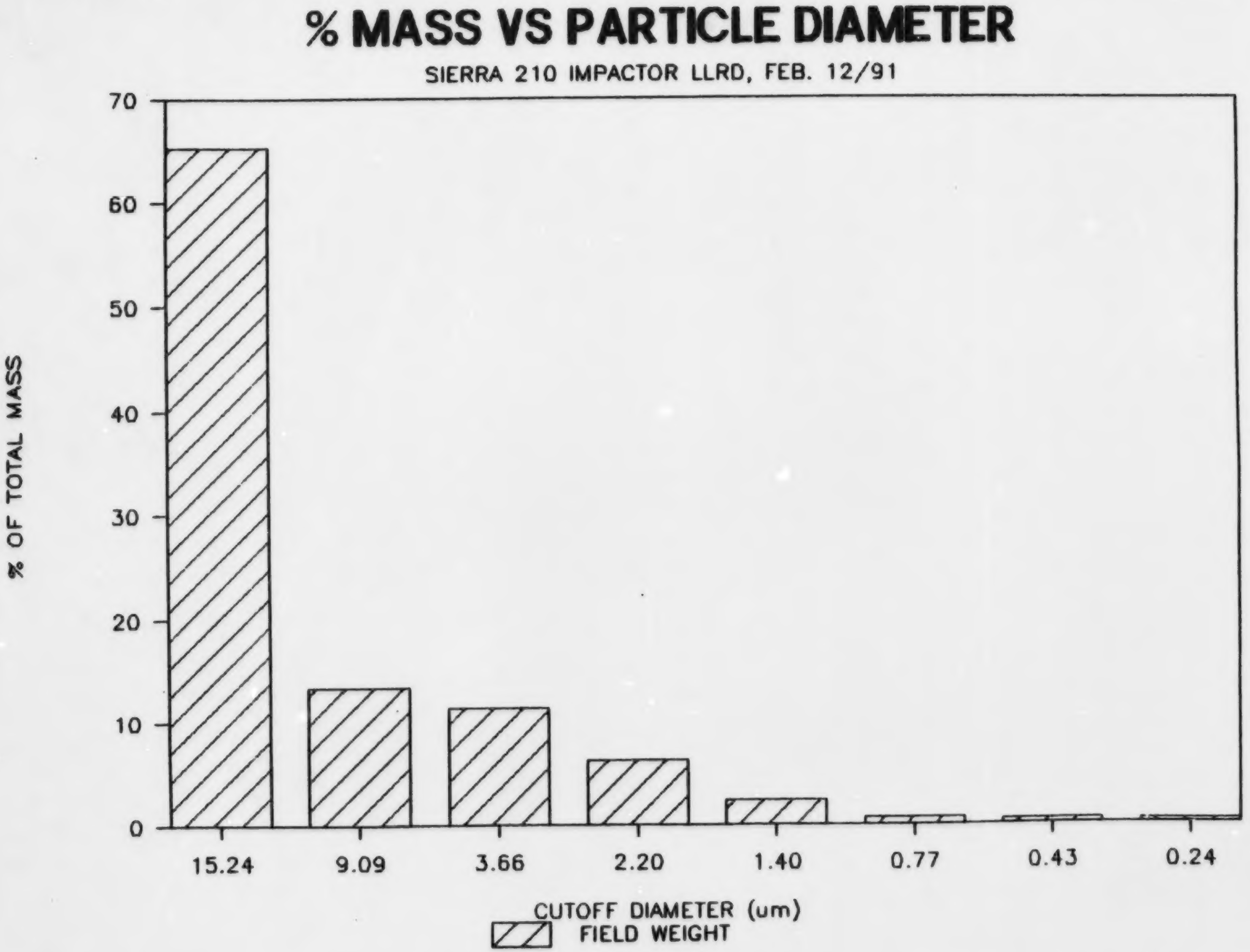


Fig. A1 - Percentage of total mass versus particle cut-off diameter measured at the crusher/conveyor belt transfer point.

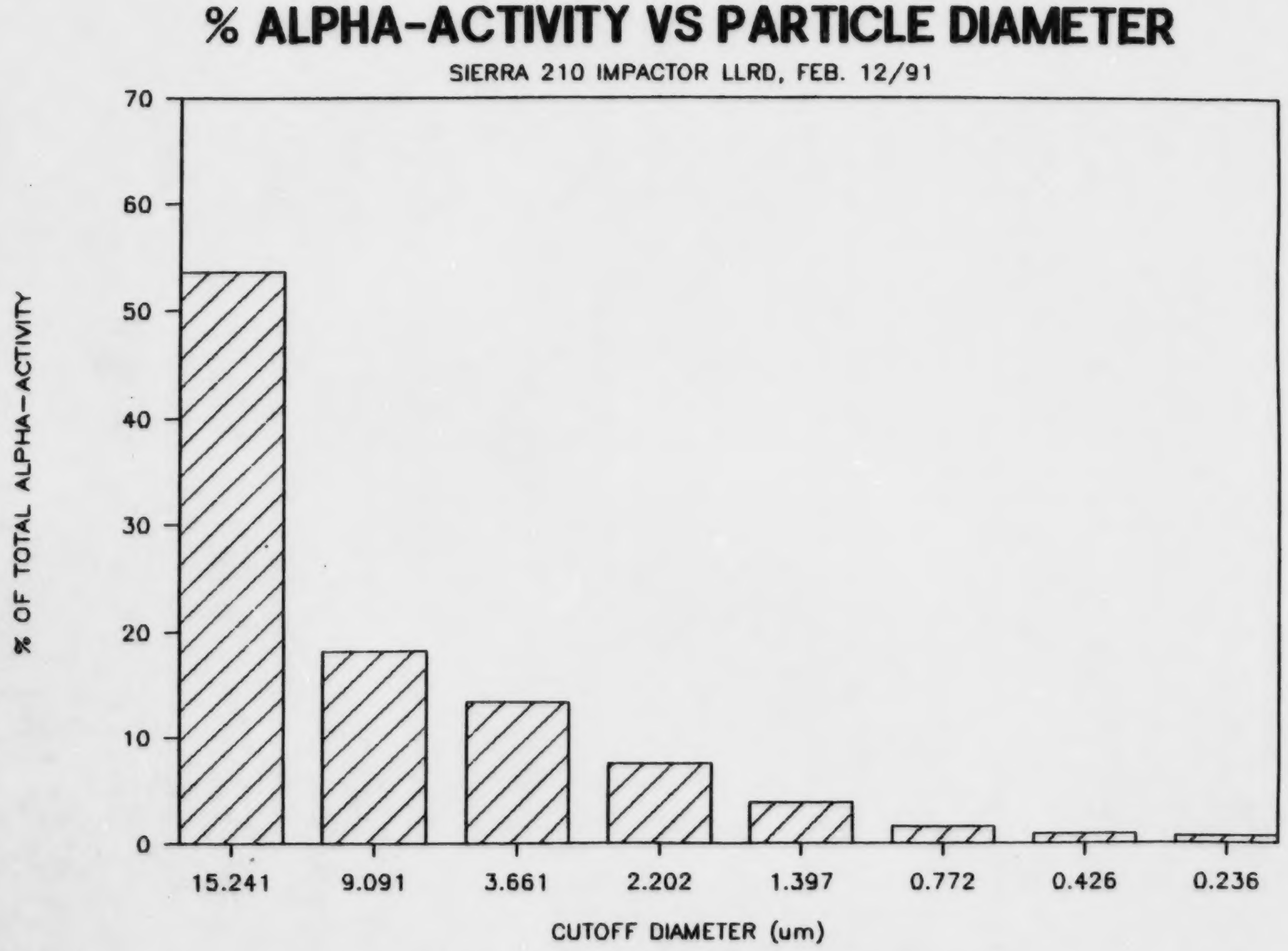


Fig. A2 - Percentage of total α-particle activity versus particle cut-off diameter measured at the crusher/conveyor transfer point.

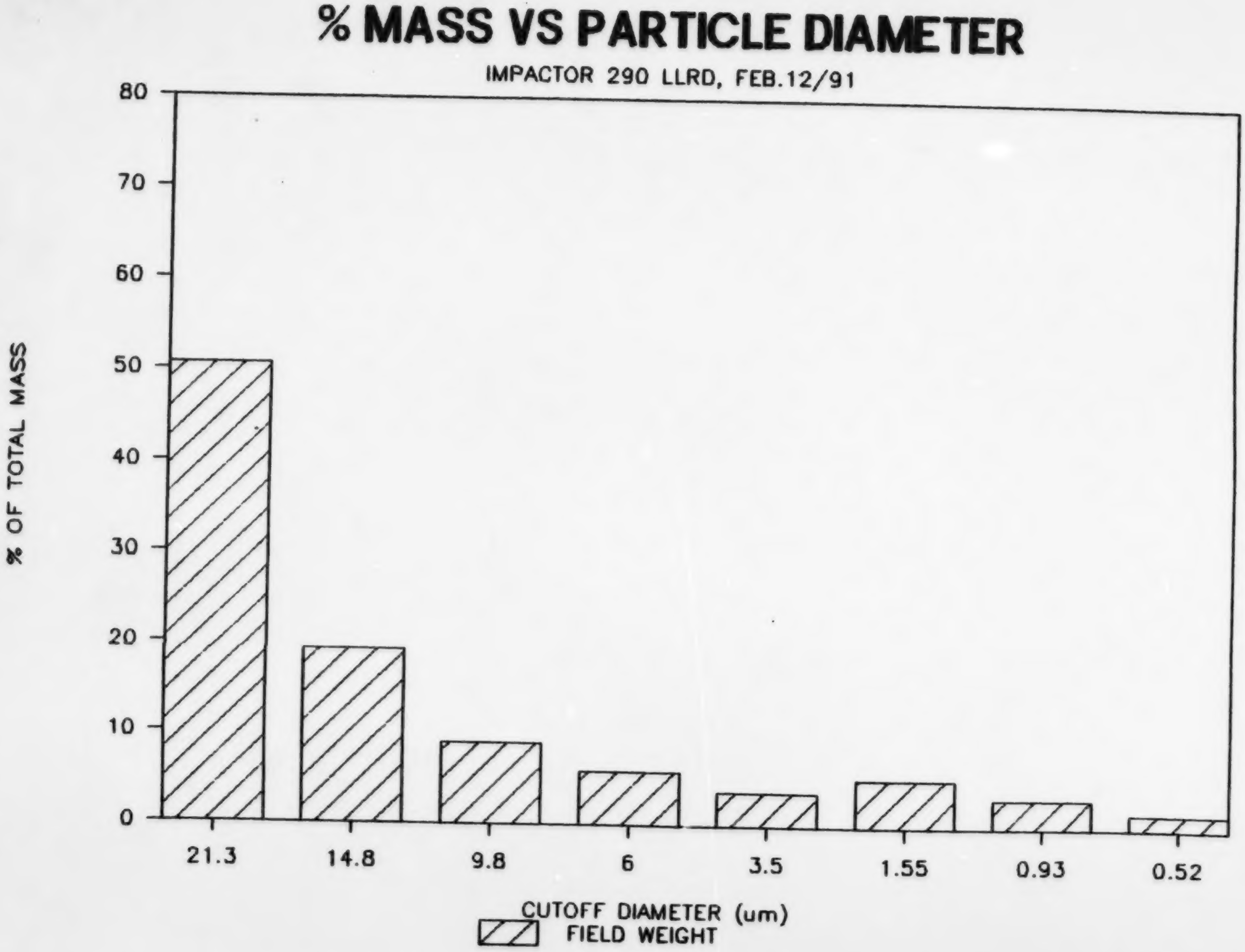


Fig. A3 - Percentage of total mass versus particle cut-off diameter measured at the crusher/conveyor belt transfer point.

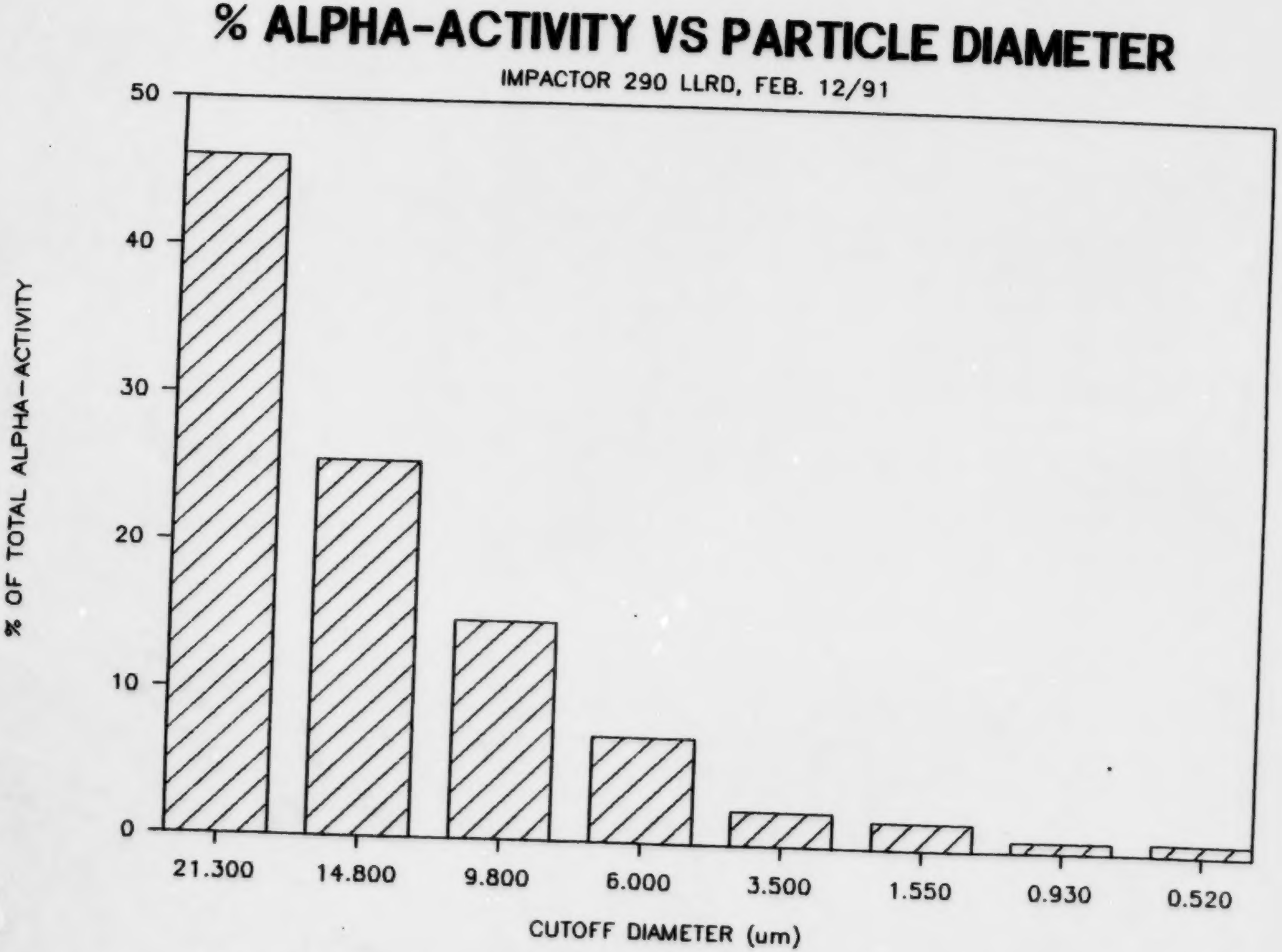


Fig. A4 - Percentage of total α-particle activity versus particle cut-off diameter measured at the crusher/conveyor belt transfer point.

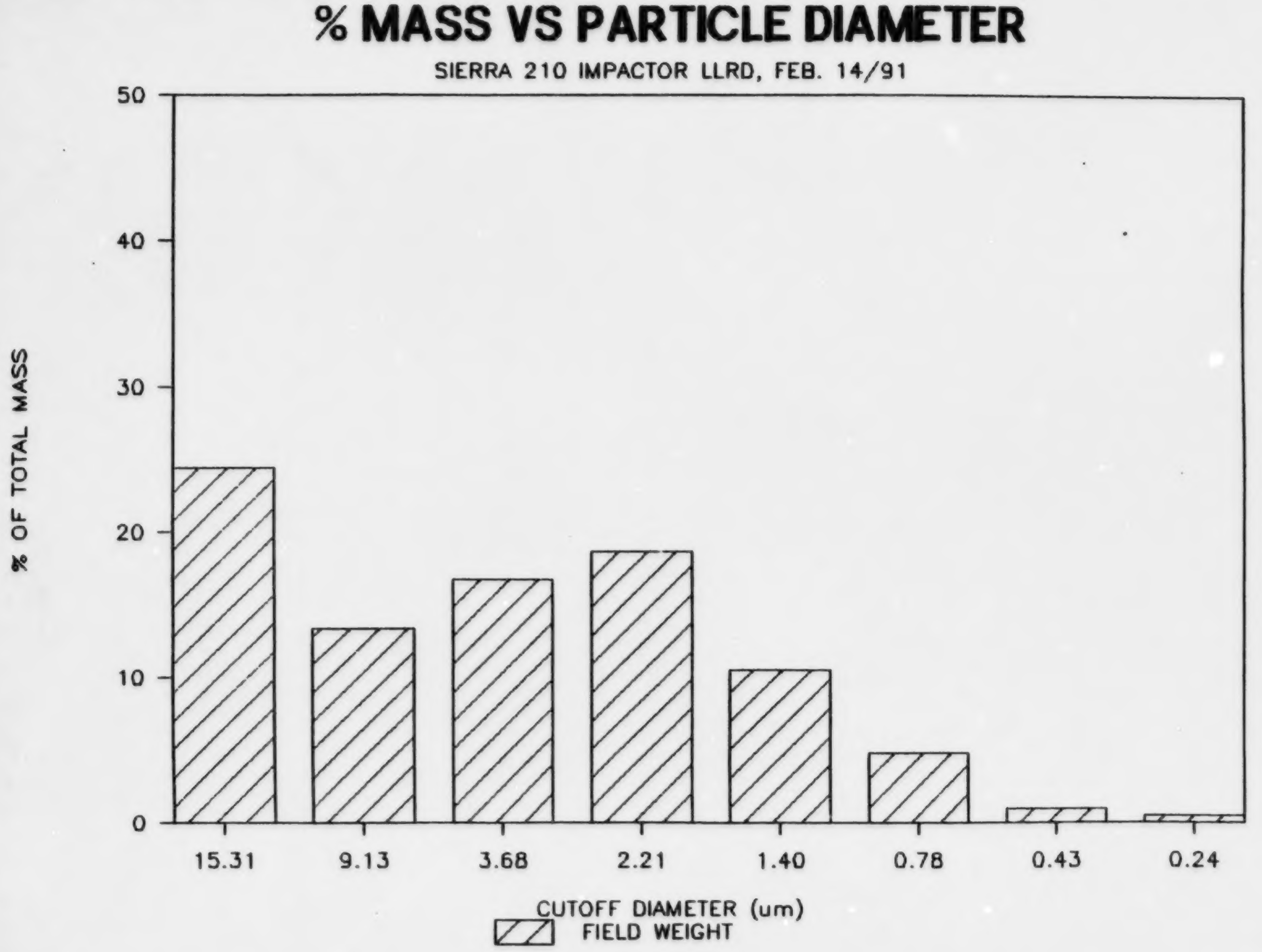


Fig. A5 - Percentage of total mass versus particle cut-off diameter measured during the ball milling operation.

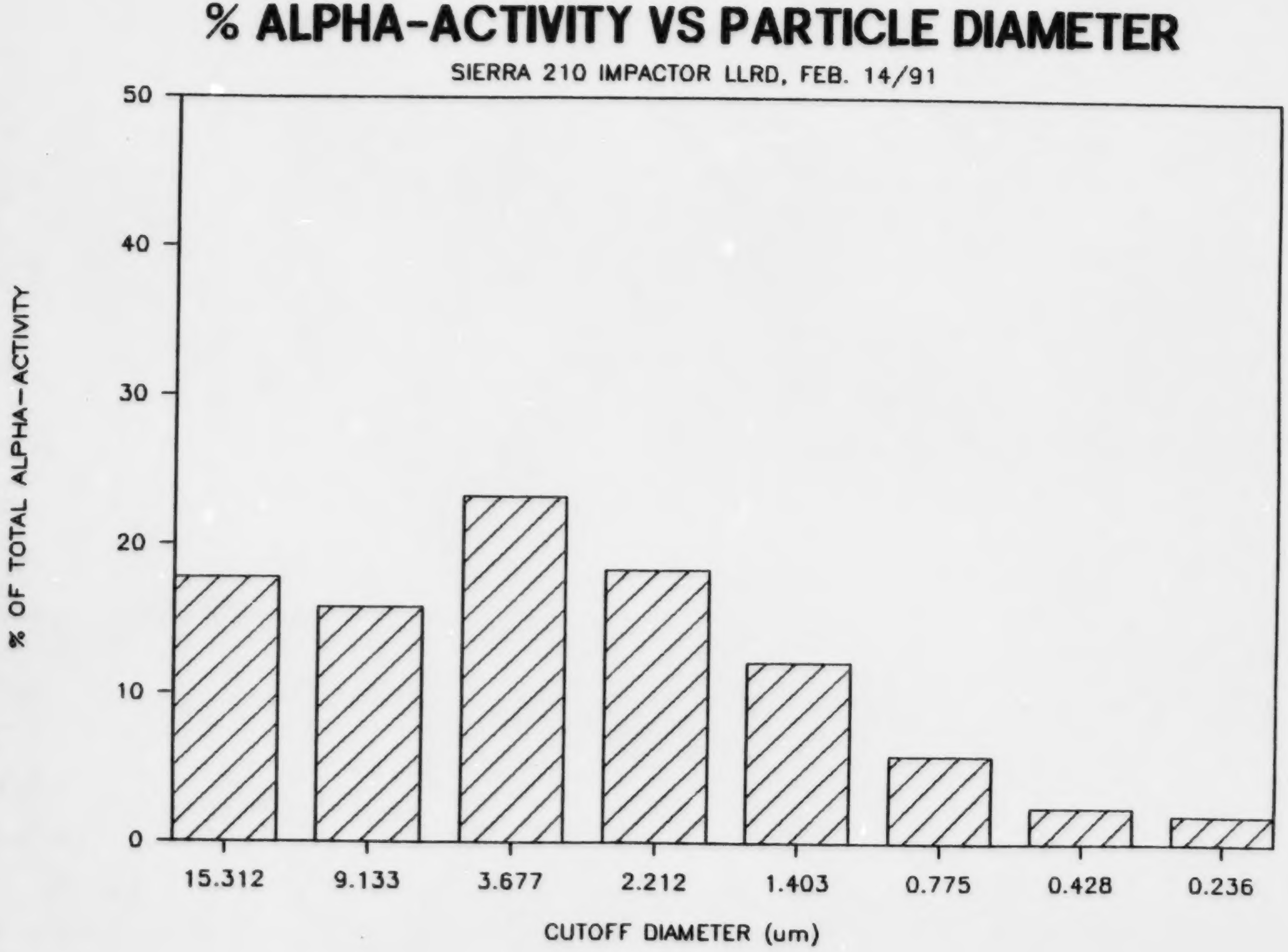


Fig. A6 - Percentage of total α-particle activity versus particle cut-off diameter measured during the ball milling operation.

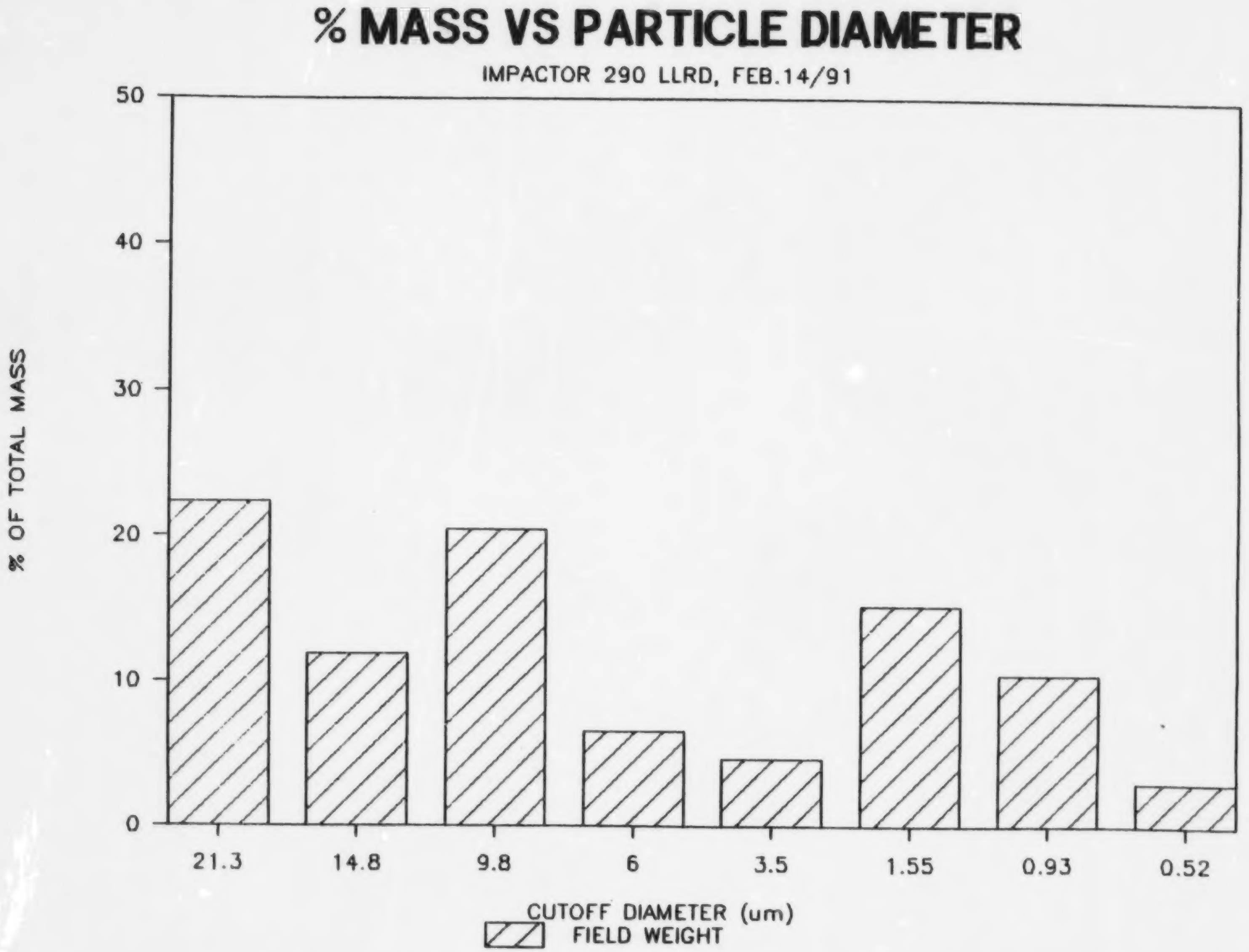


Fig. A7 - Percentage of total mass versus particle cut-off diameter measured during the ball milling operation.

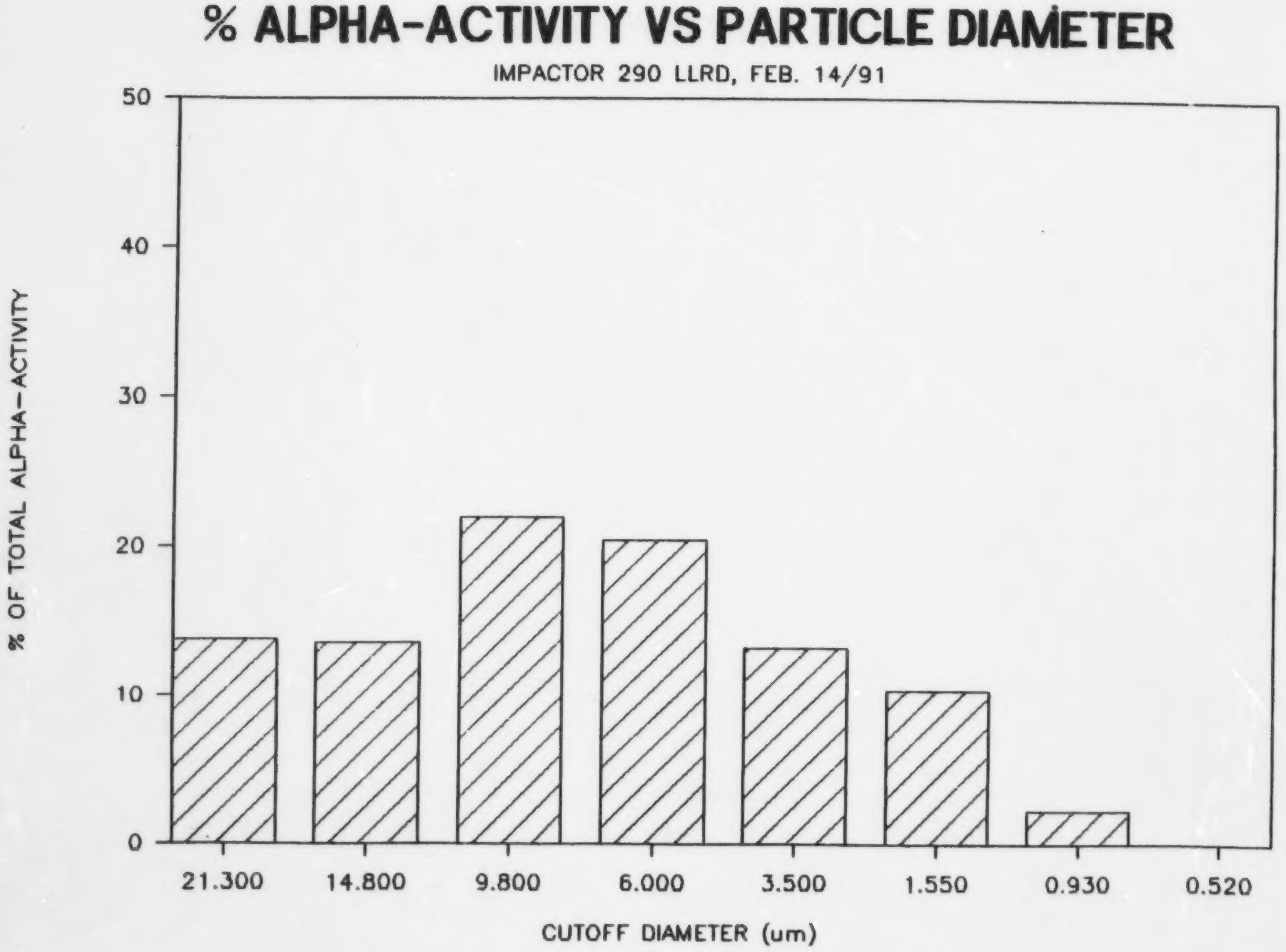


Fig. A8 - Percentage of total α-particle activity versus particle cut-off diameter measured during the ball milling operation.

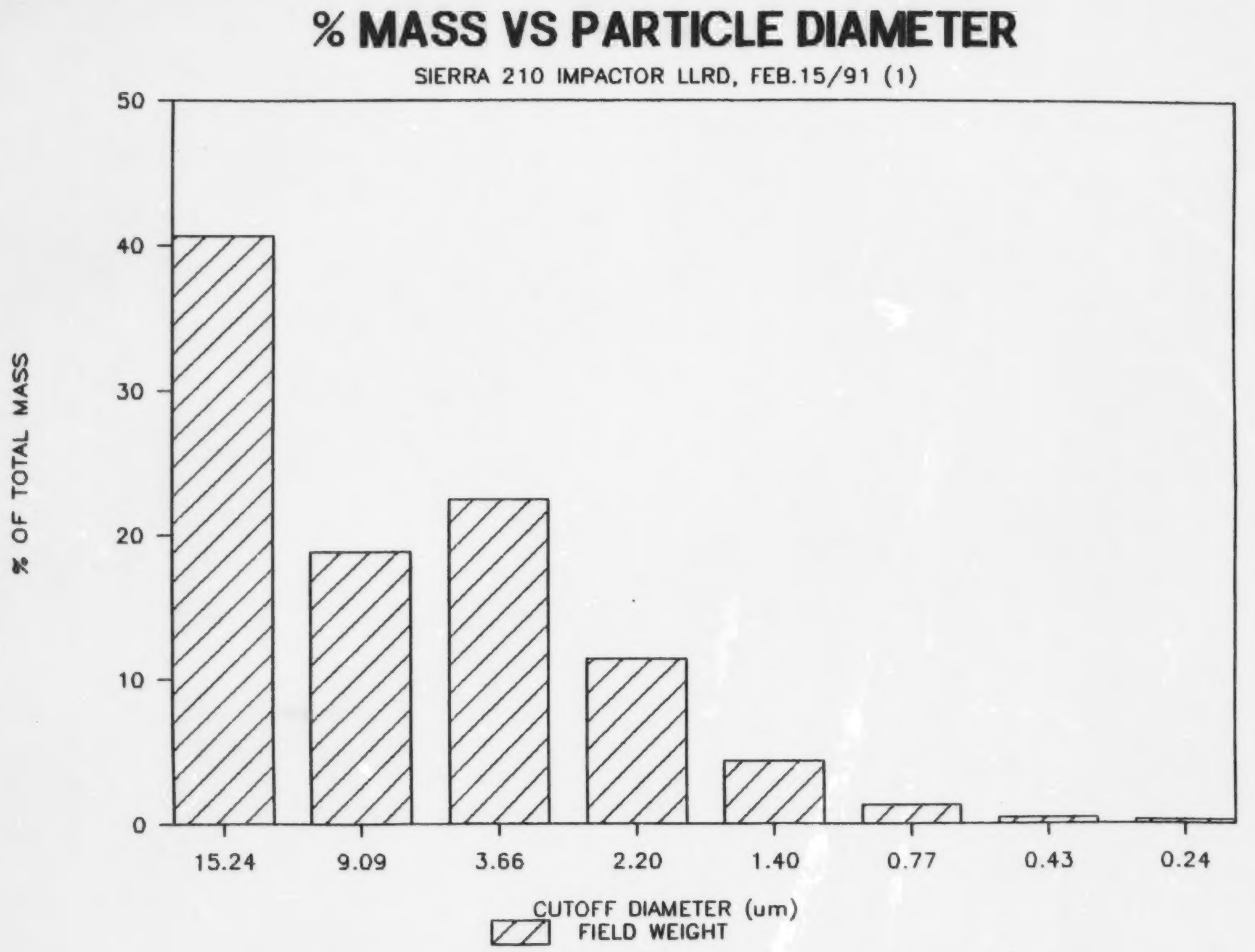


Fig. A9 - Percentage of total mass versus particle cut-off diameter measured during the cone crushing operation.

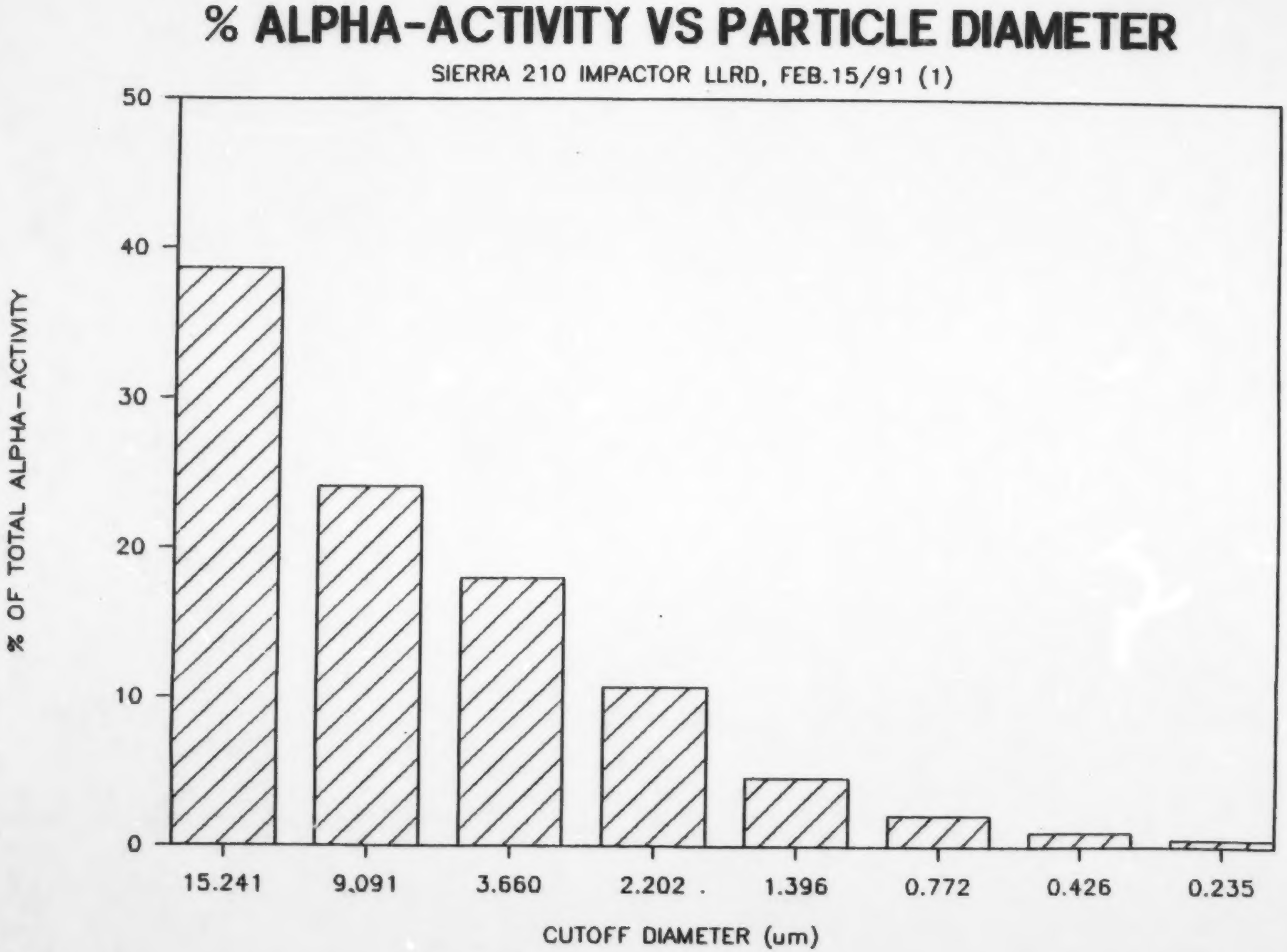


Fig. A10 - Percentage of total α-particle activity versus particle cut-off diameter measured during the ball milling operation.

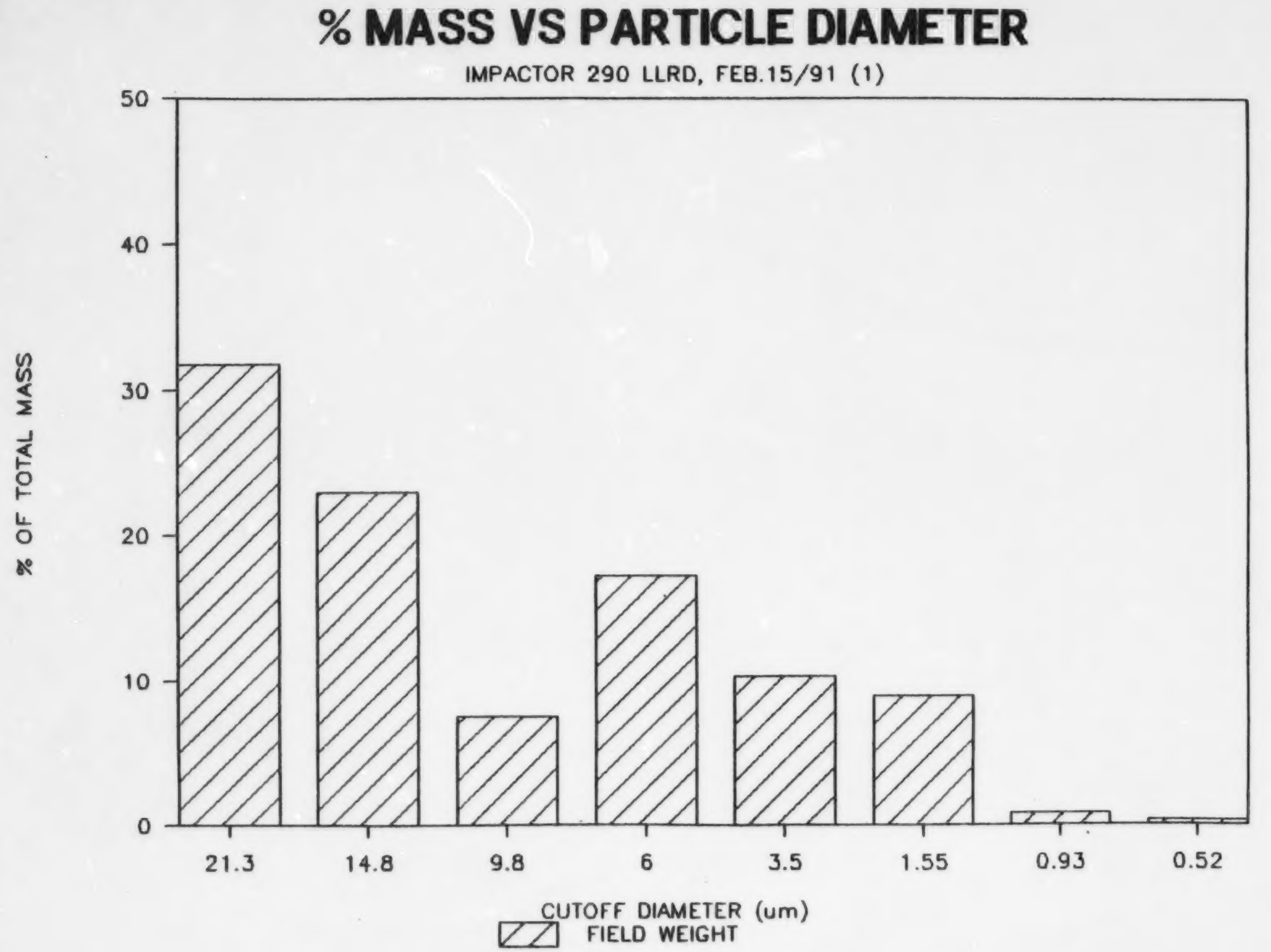


Fig. A11 - Percentage of total mass versus particle cut-off diameter measured during the cone crushing operation.

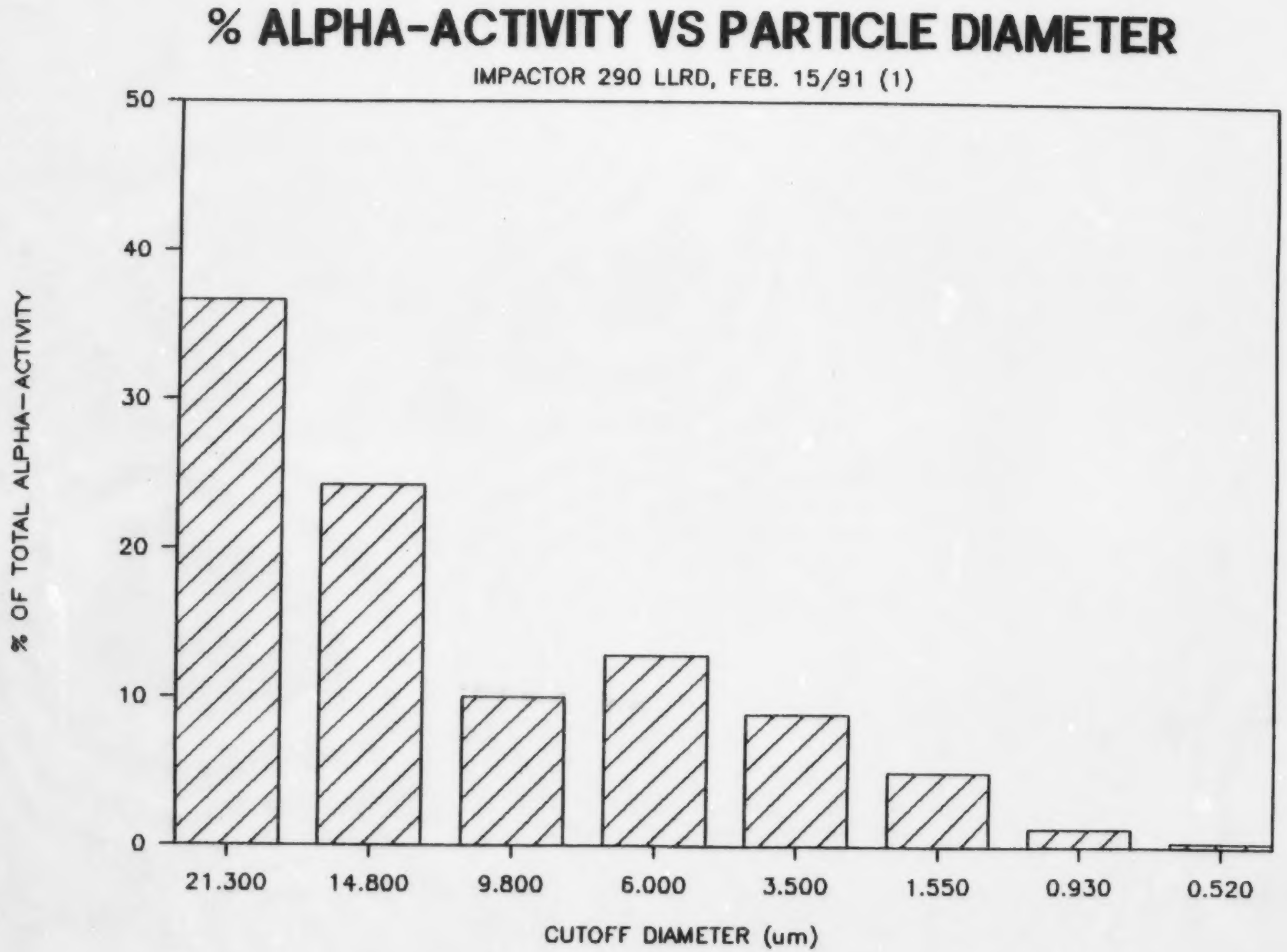


Fig. A12 - Percentage of total α-particle activity versus particle cut-off diameter measured during the ball milling operation.

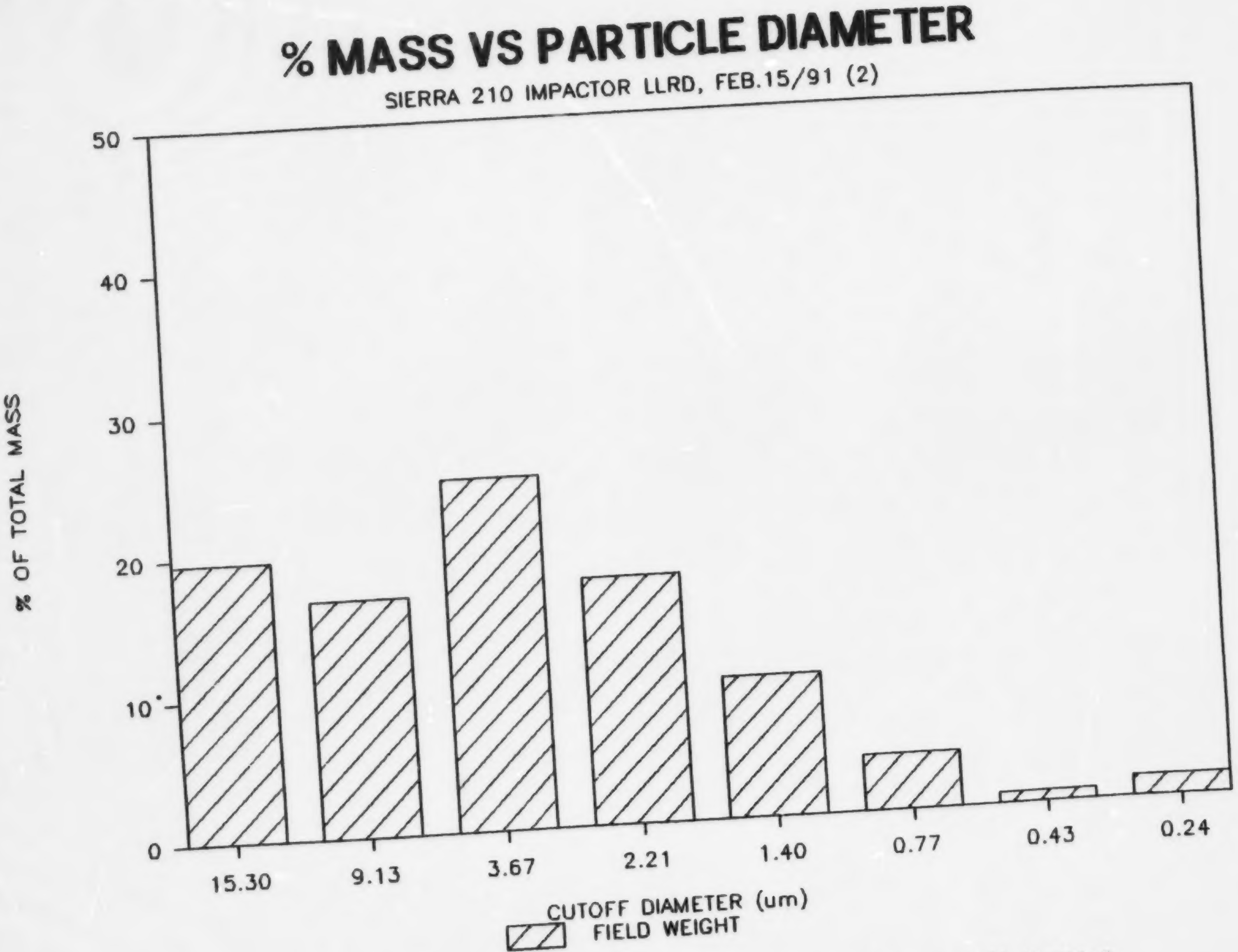


Fig. A13 - Percentage of total mass versus particle cut-off diameter measured during the yellowcake precipitation operation.

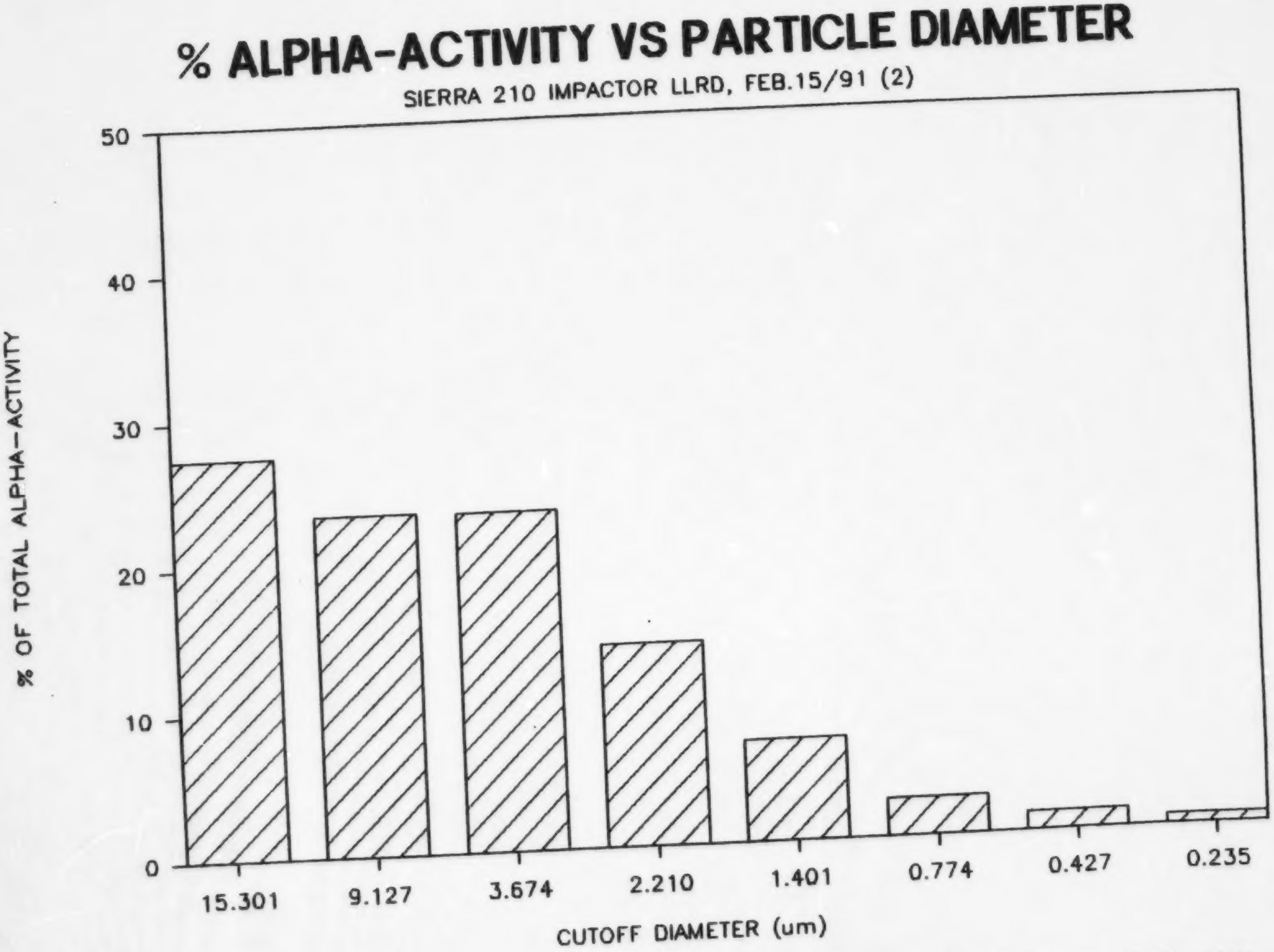


Fig. A14 - Percentage of total α-particle activity versus particle cut-off diameter measured during the yellowcake precipitation operation.

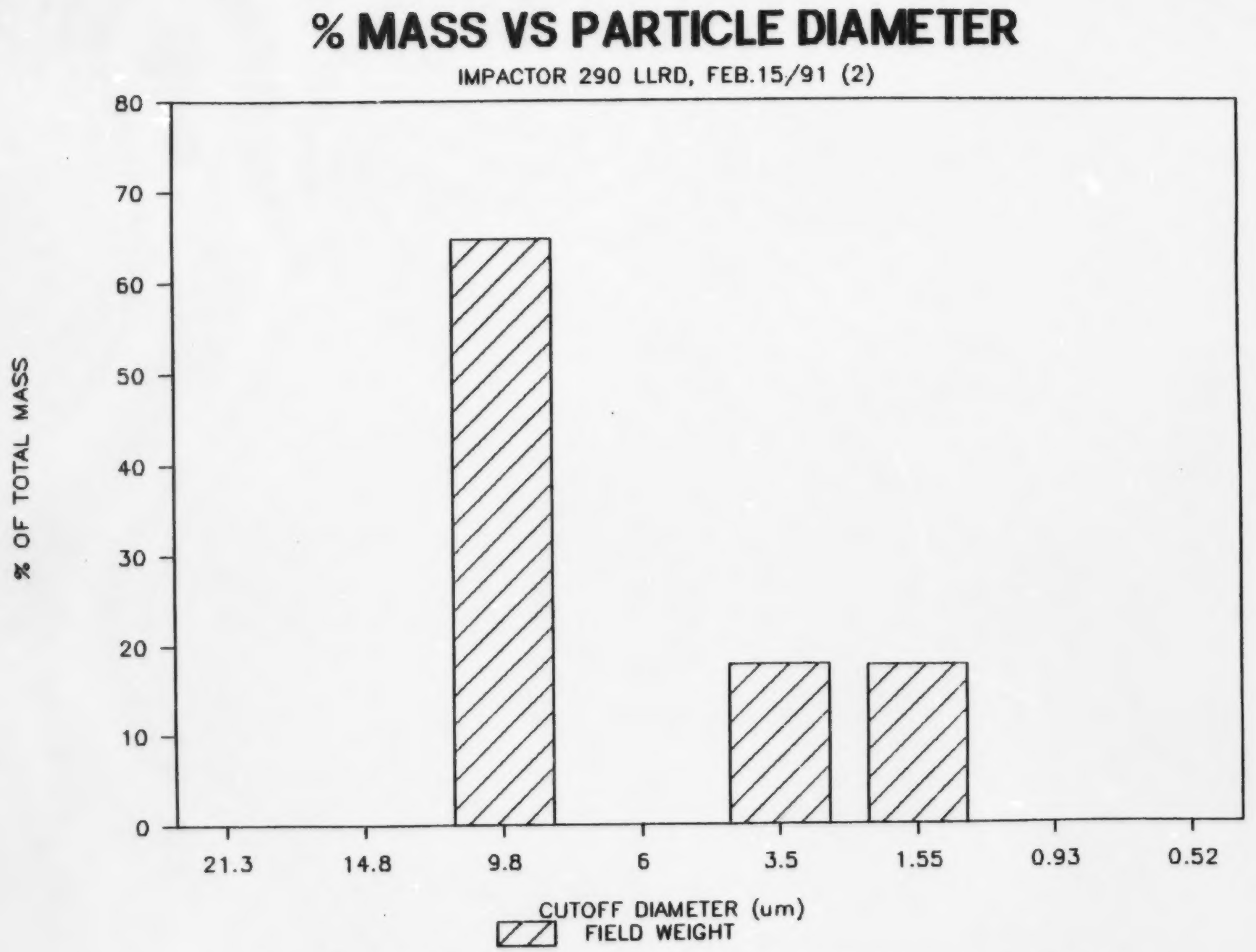


Fig. A15 - Percentage of total mass versus particle cut-off diameter measured during the yellowcake precipitation operation.

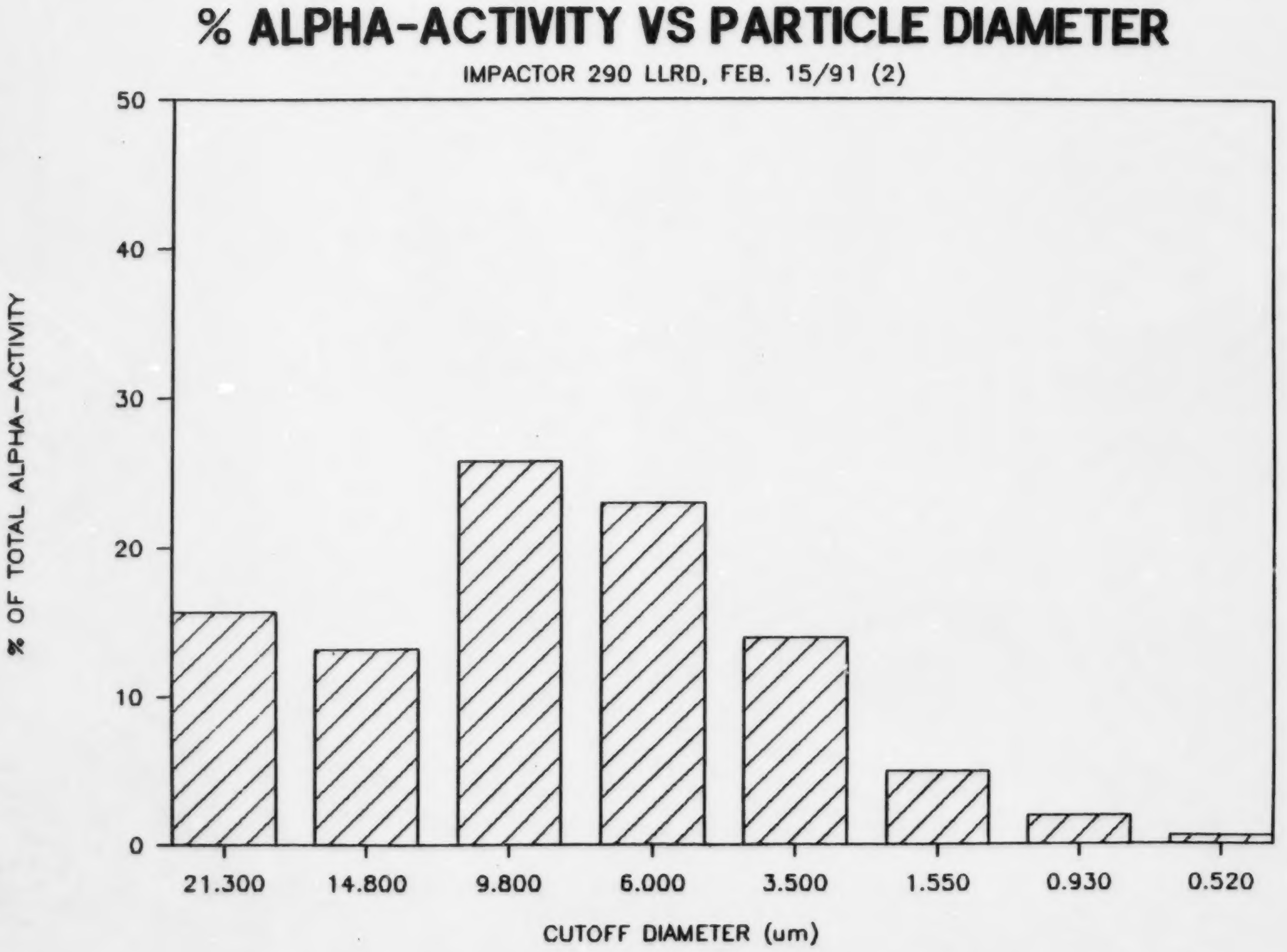


Fig. A16 - Percentage of total α-particle activity versus particle cut-off diameter measured during the yellowcake precipitation operation.

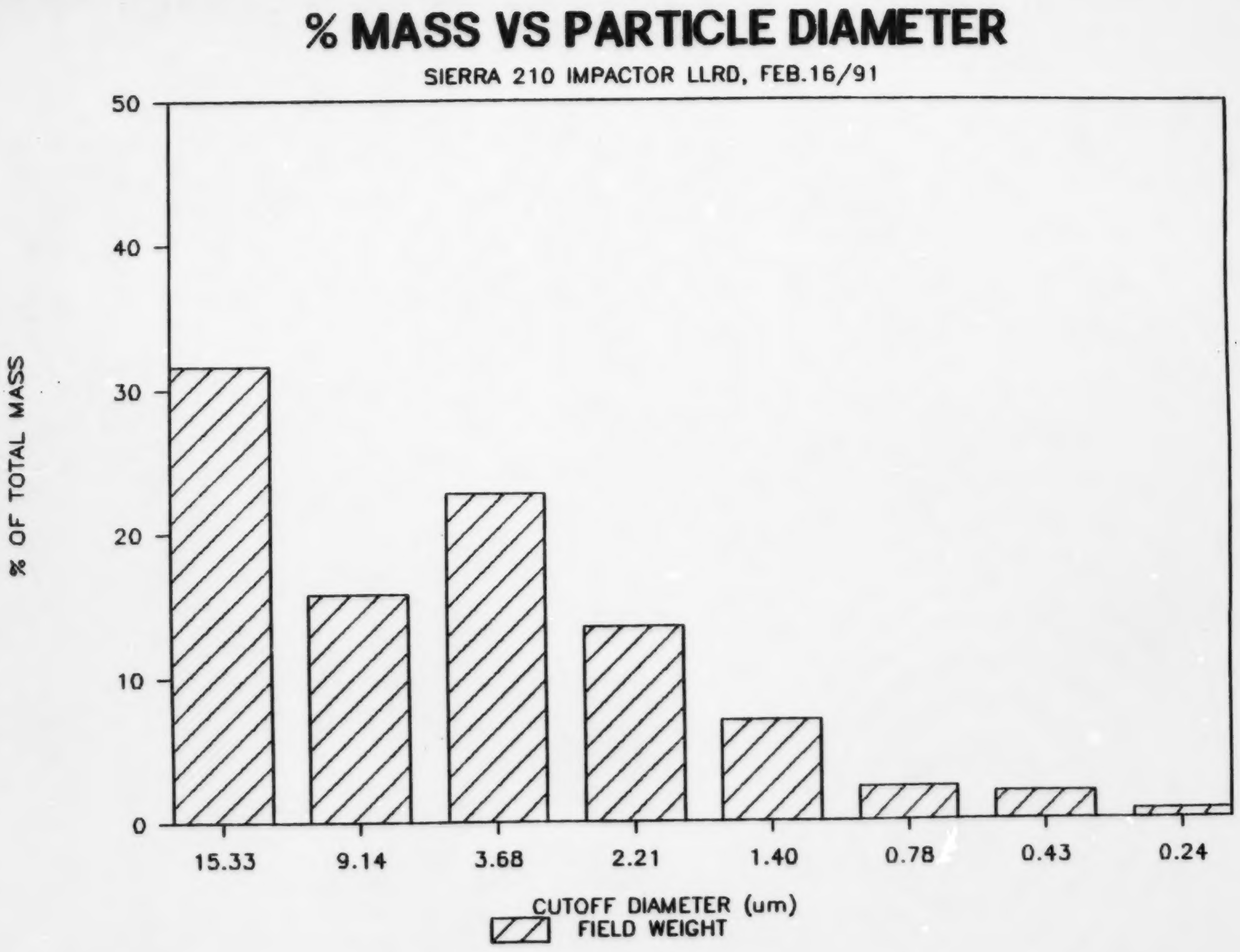


Fig. A17 - Percentage of total mass versus particle cut-off diameter measured at the hopper/ball mill/conveyor belt area.

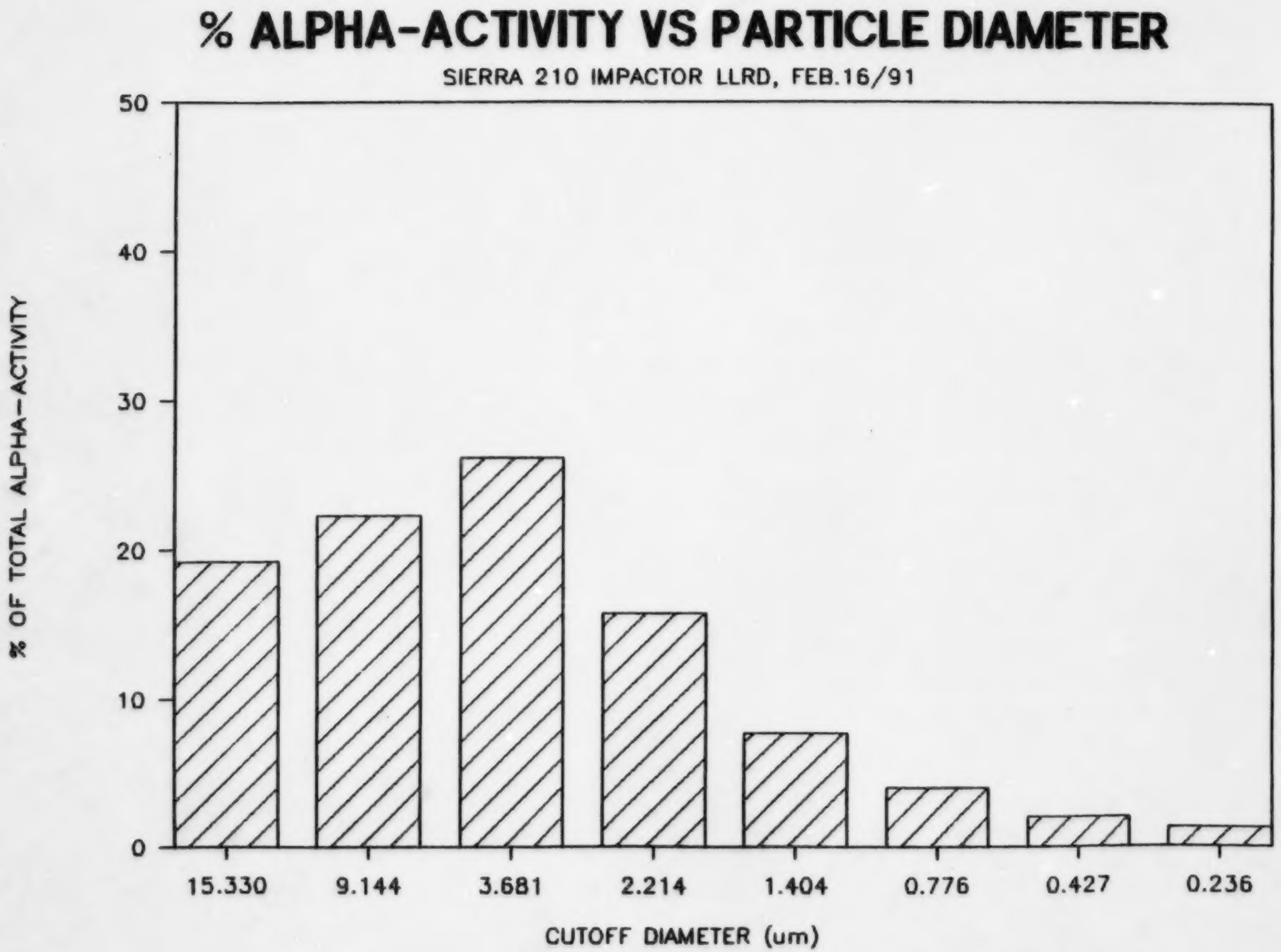


Fig. A18 - Percentage of total α-particle activity versus particle cut-off diameter measured at the hopper/ball mill/conveyor belt area.

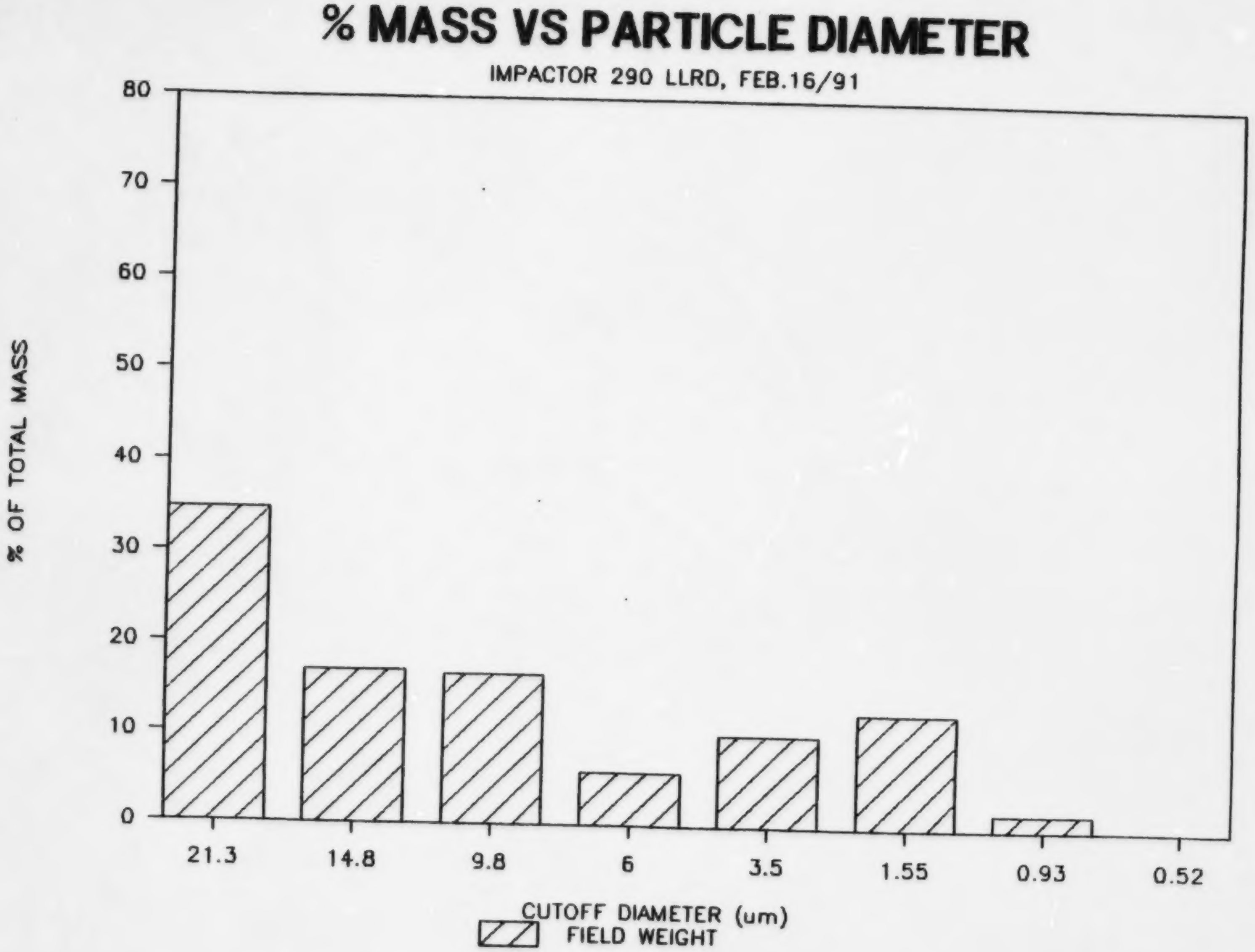


Fig. A19 - Percentage of total mass versus particle cut-off diameter measured at the hopper/ball mill/conveyor belt area.

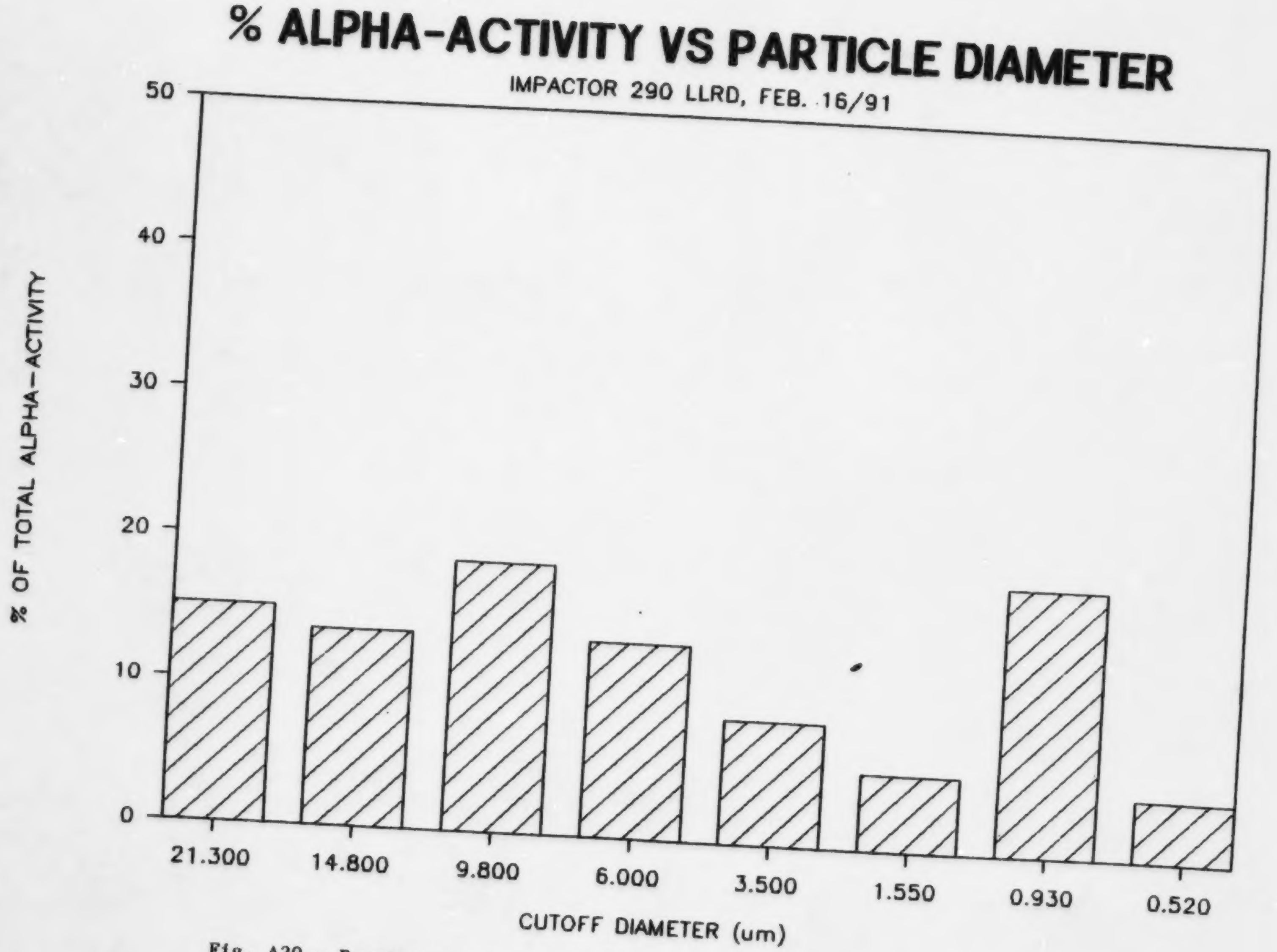


Fig. A20 - Percentage of total α-particle activity versus particle cut-off diameter measured at the hopper/ball mill/conveyor belt area.

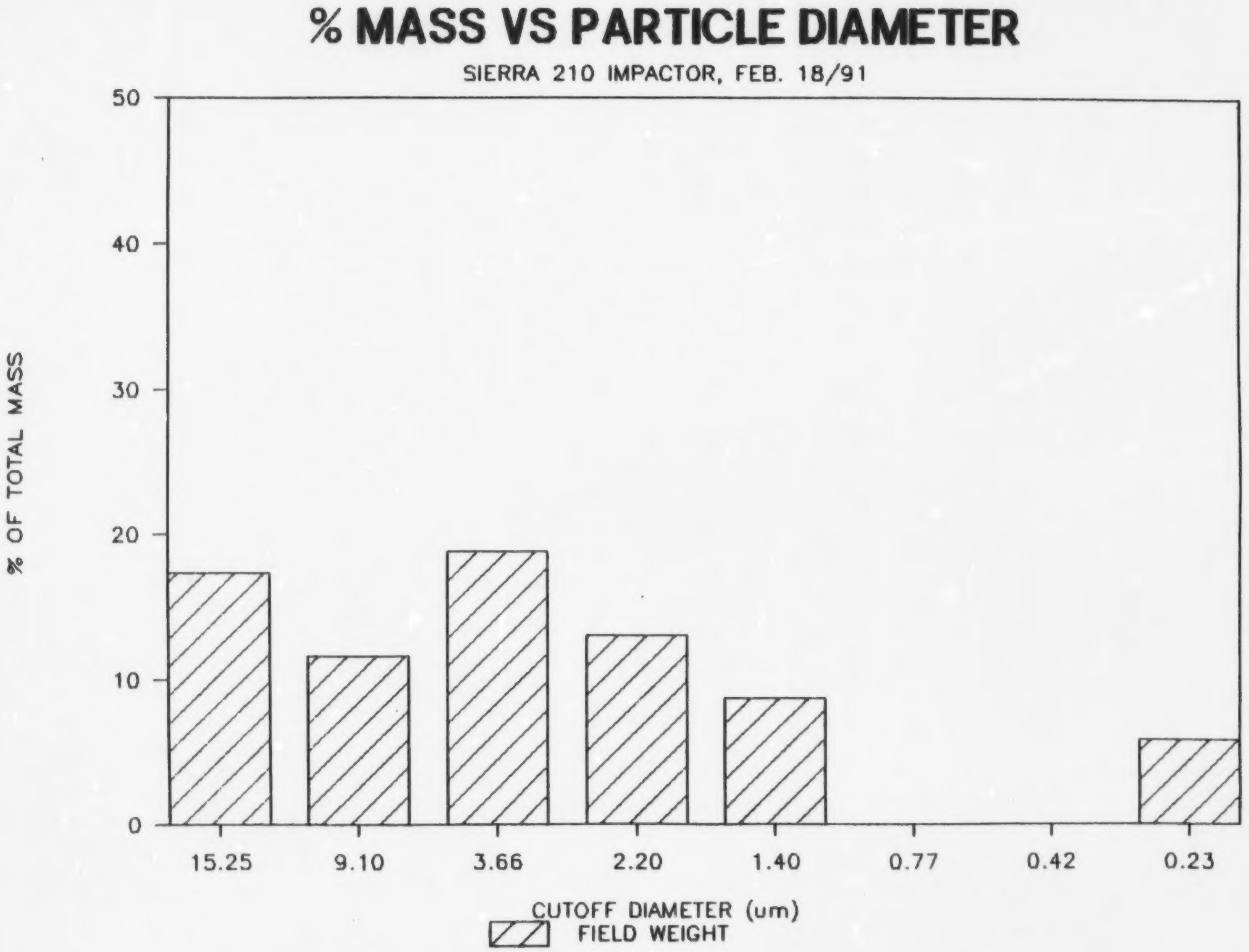


Fig. A21 - Percentage of total mass versus particle cut-off diameter measured during the S.A.G. milling operation.

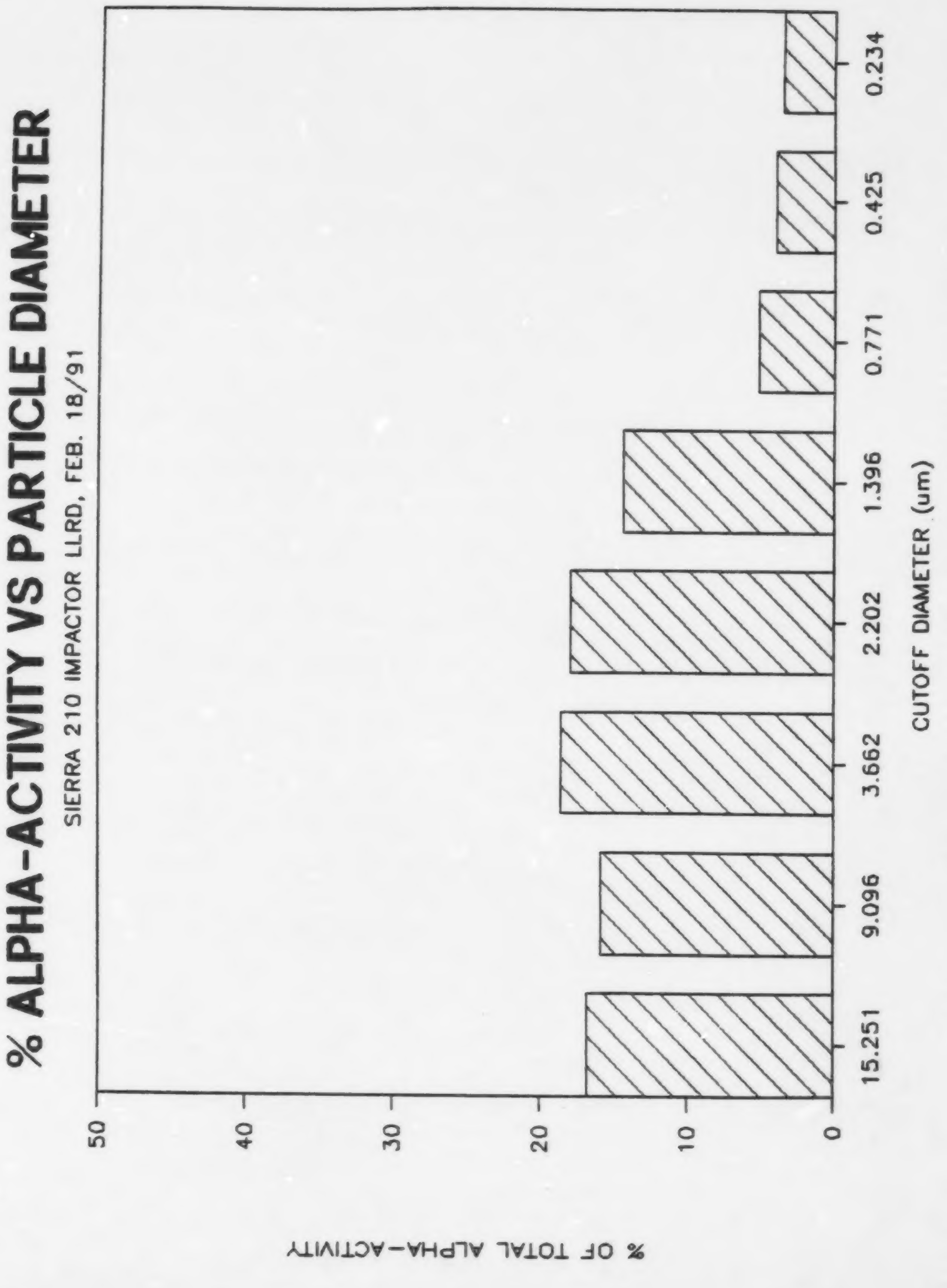


Fig. A22 - Percentage of total α-particle activity versus particle cut-off diameter measured during the S.A.G. milling operation.

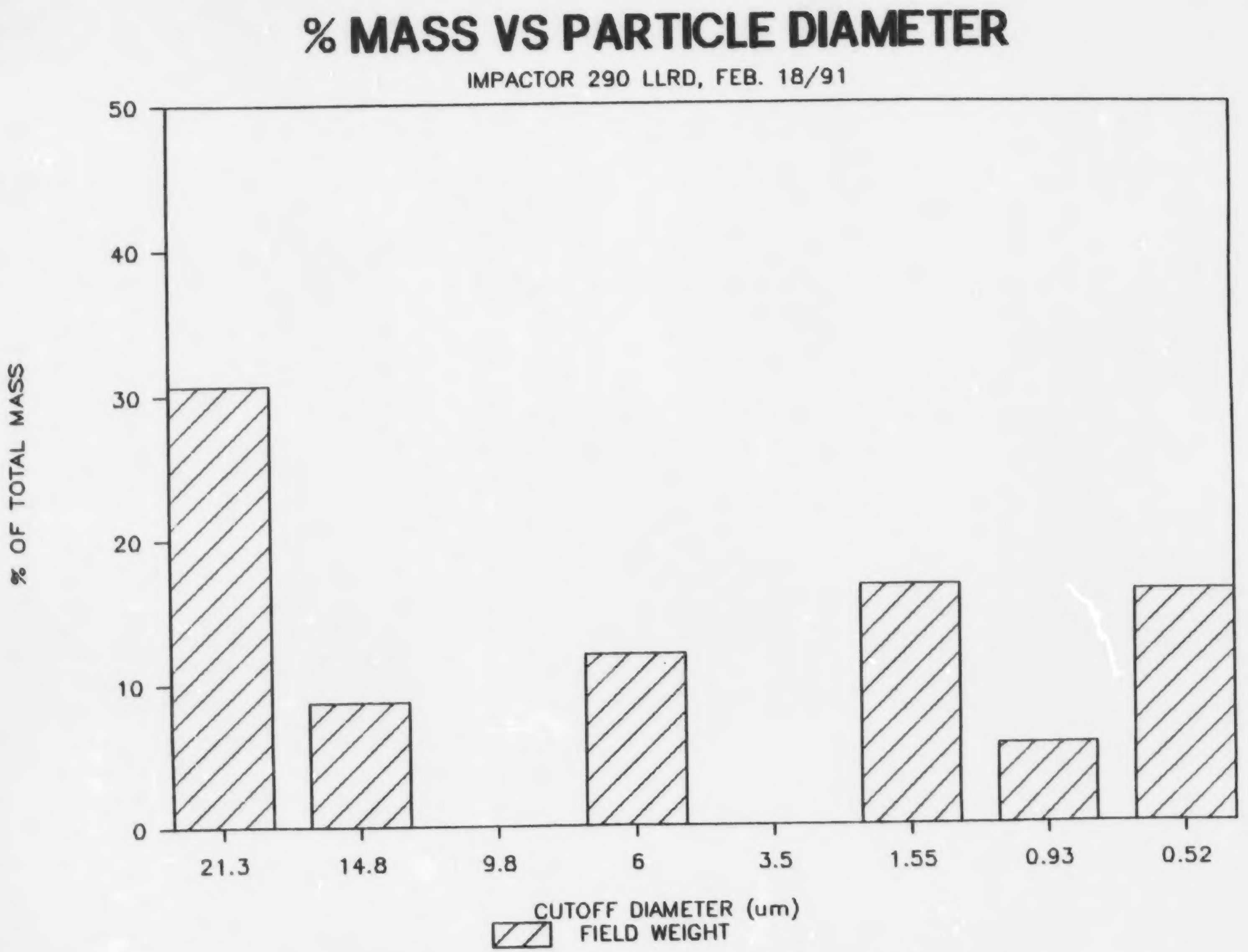


Fig. A23 - Percentage of total mass versus particle cut-off diameter measured during the S.A.G. milling operation.

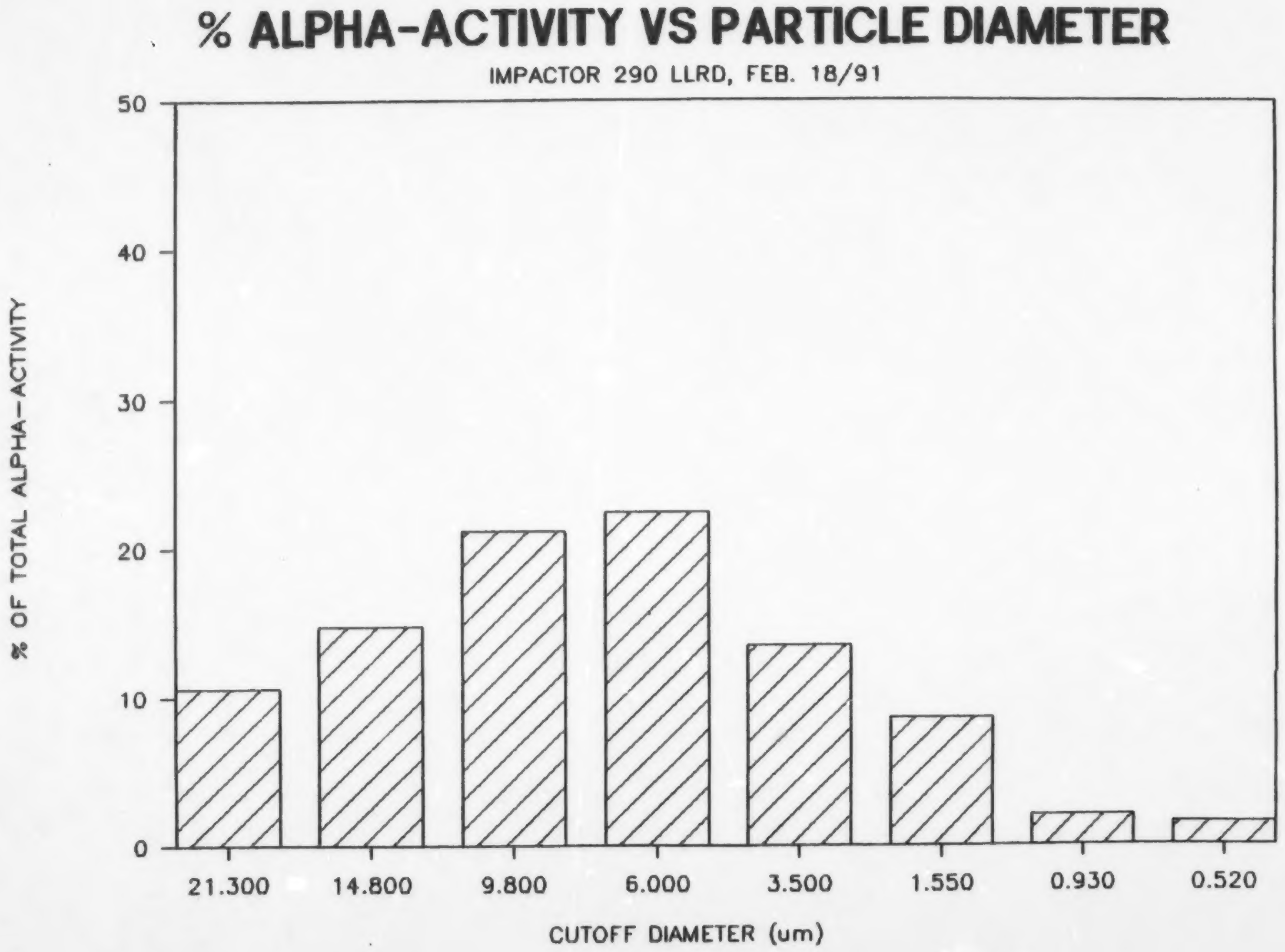


Fig. A24 - Percentage of total α-particle activity versus particle cut-off diameter measured during the S.A.G. milling operation.

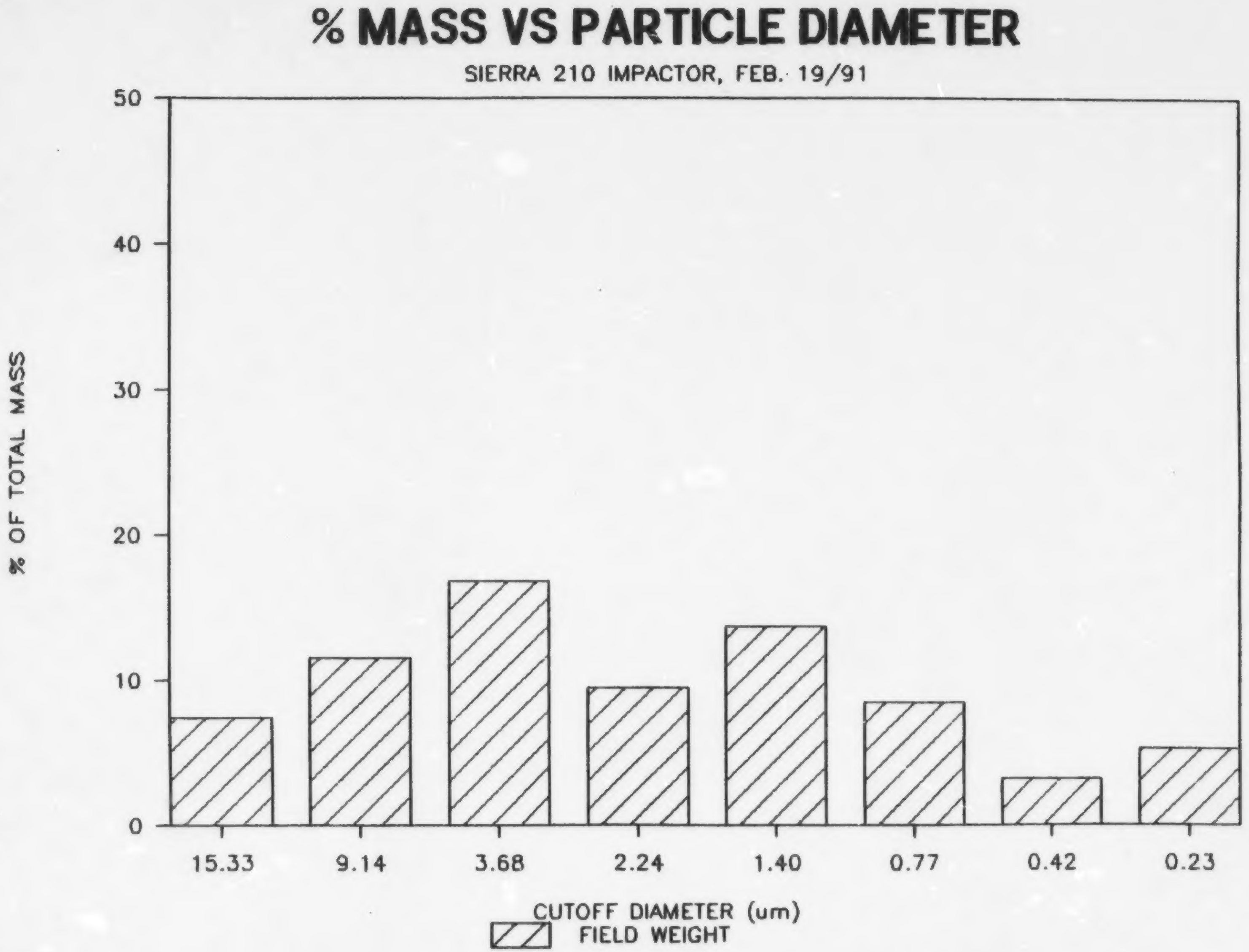


Fig. A25 - Percentage of total mass versus particle cut-off diameter measured during the lime slaking operation.

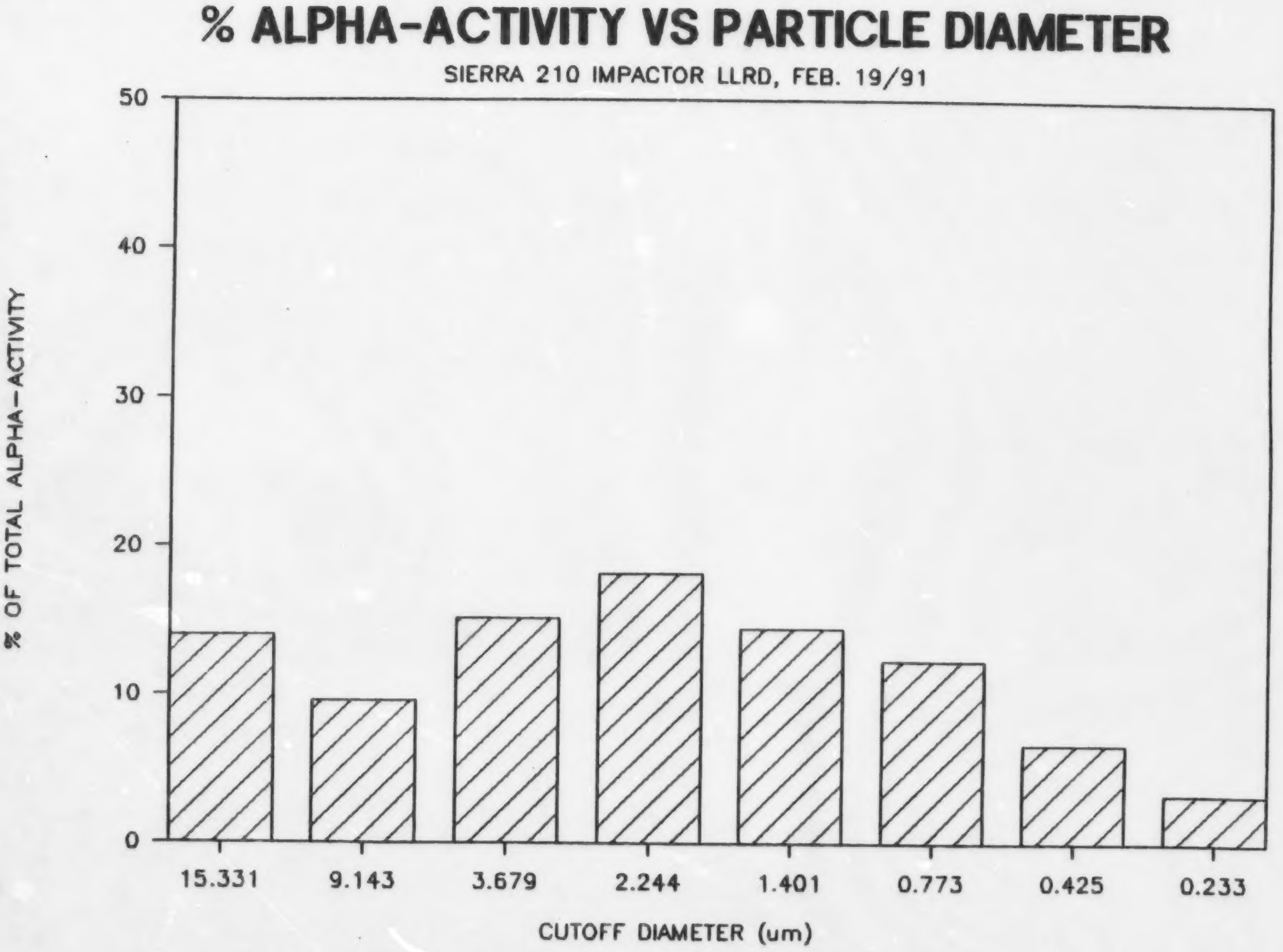


Fig. A26 - Percentage of total α-particle activity versus particle cut-off diameter measured during the lime slaking operation.

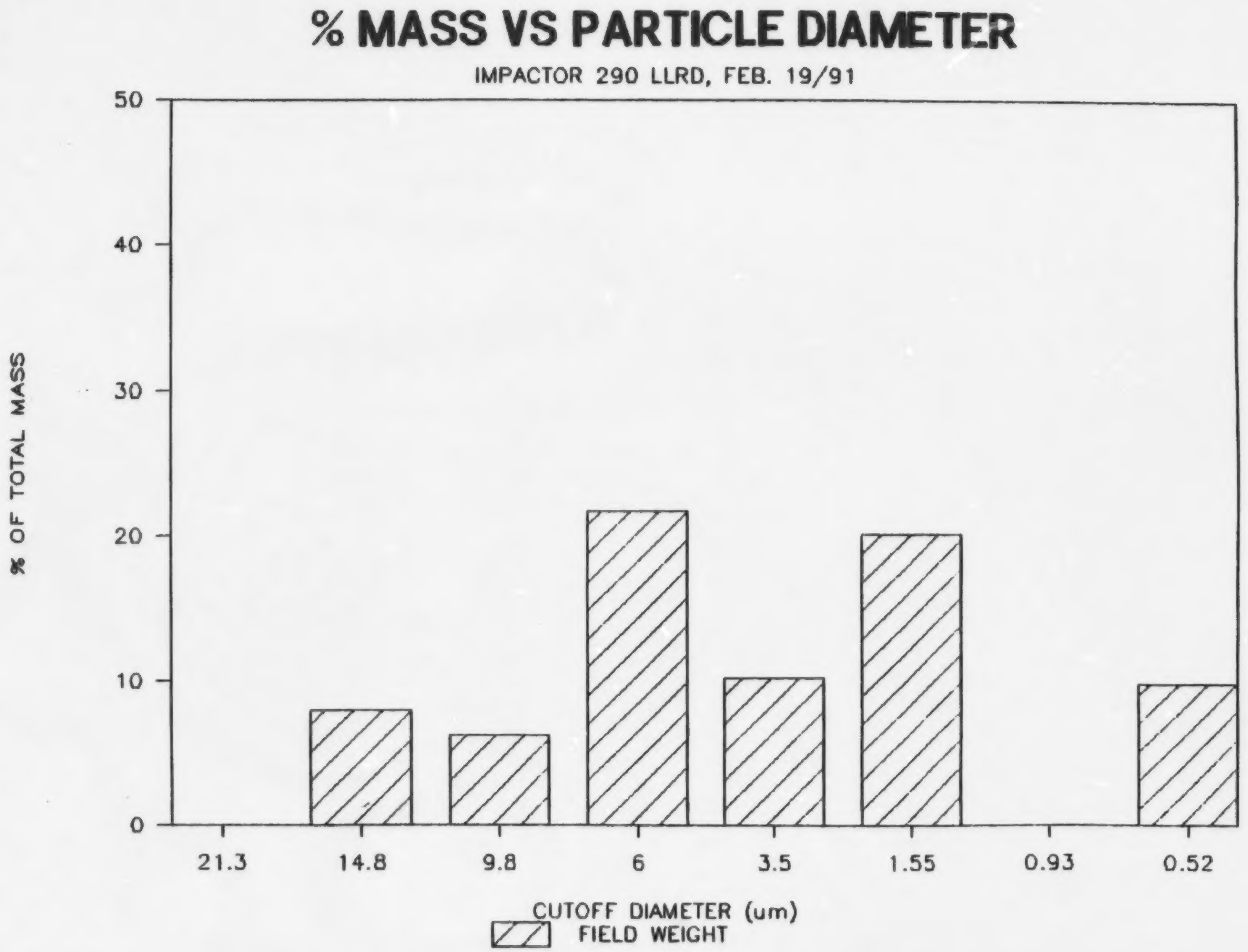


Fig. A27 - Percentage of total mass versus particle cut-off diameter measured during the lime slaking operation.

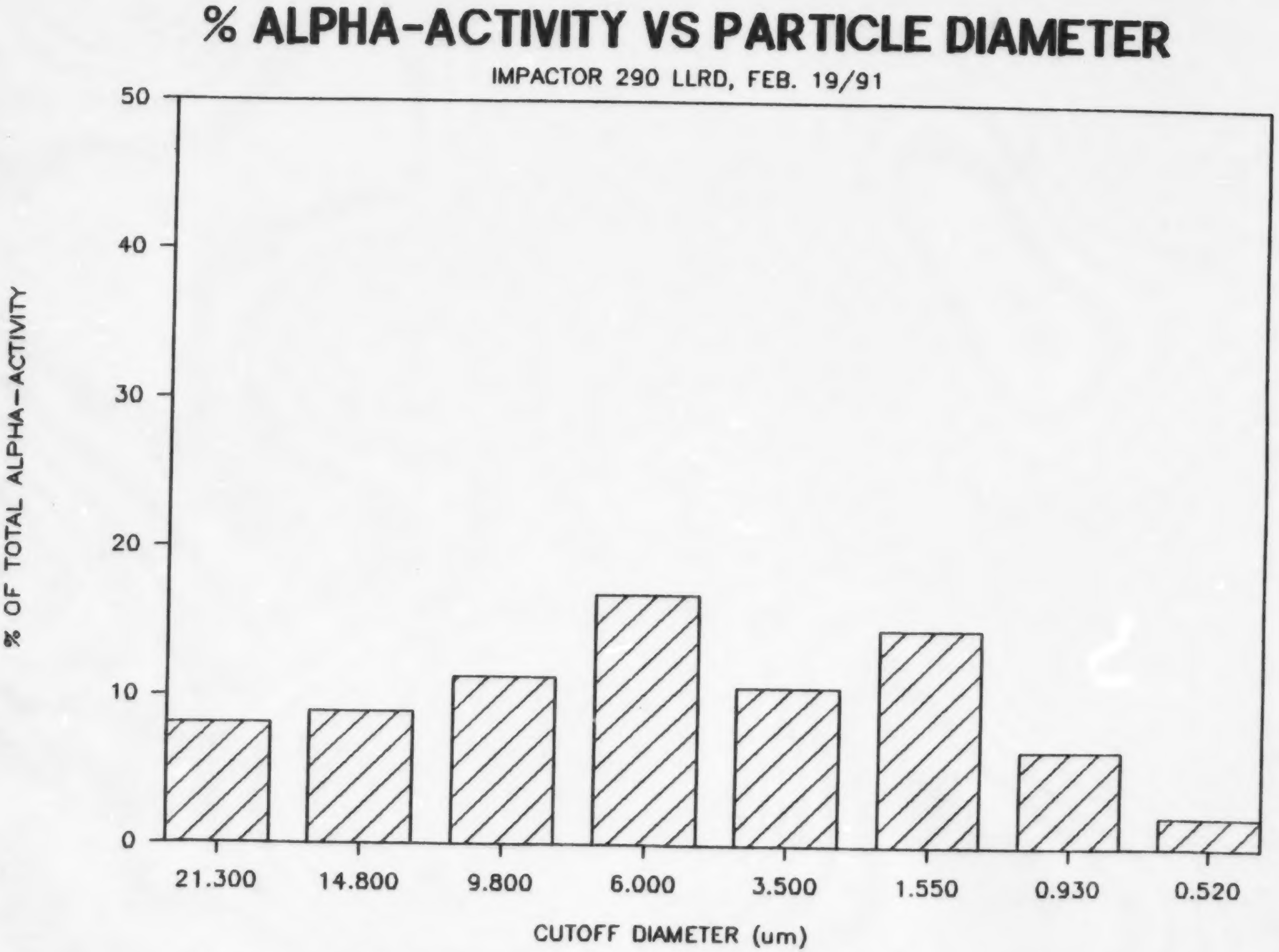


Fig. A28 - Percentage of total α-particle activity versus particle cut-off diameter measured during the lime slaking operation.

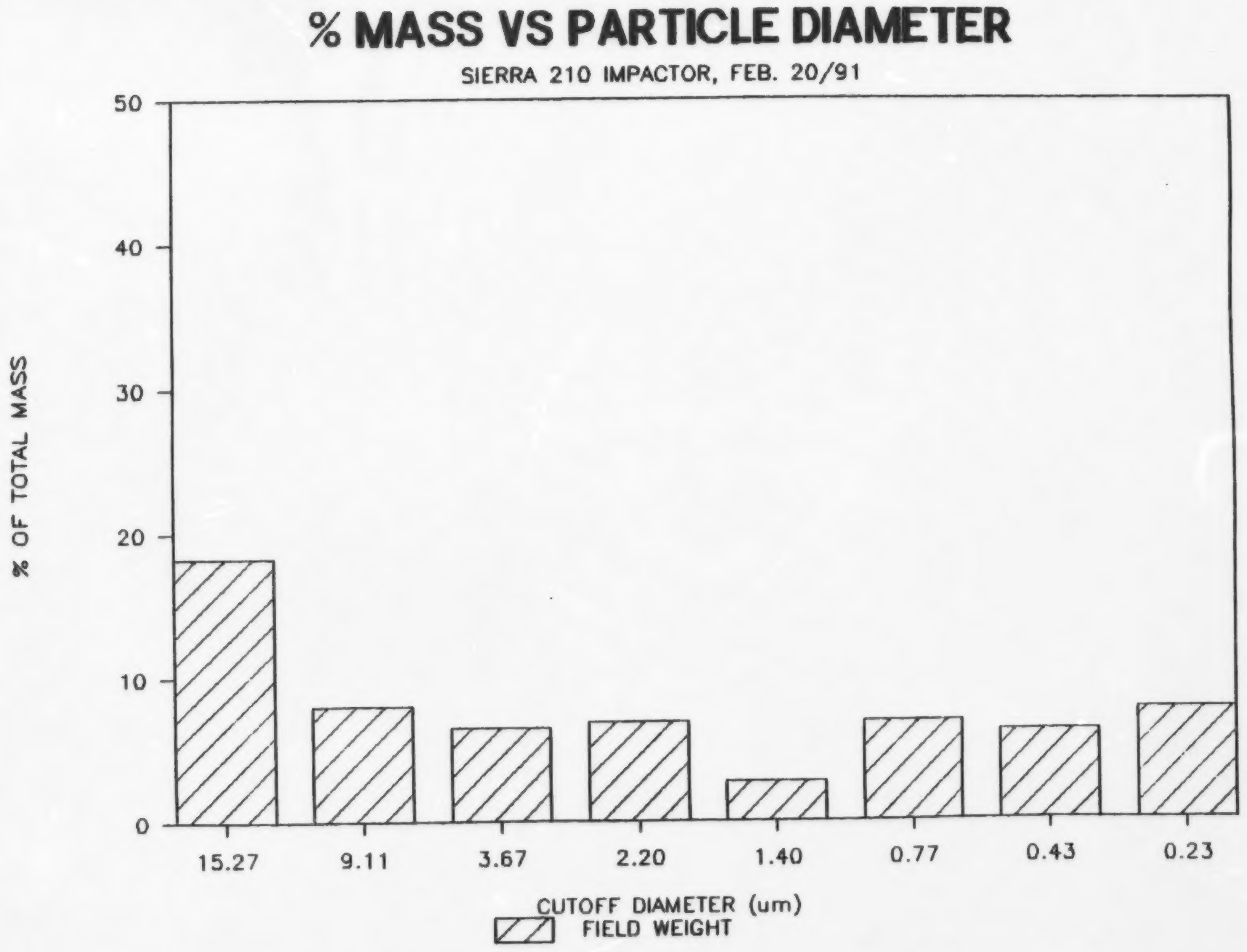


Fig. A29 - Percentage of total mass versus particle cut-off diameter measured during the yellowcake packaging operation.

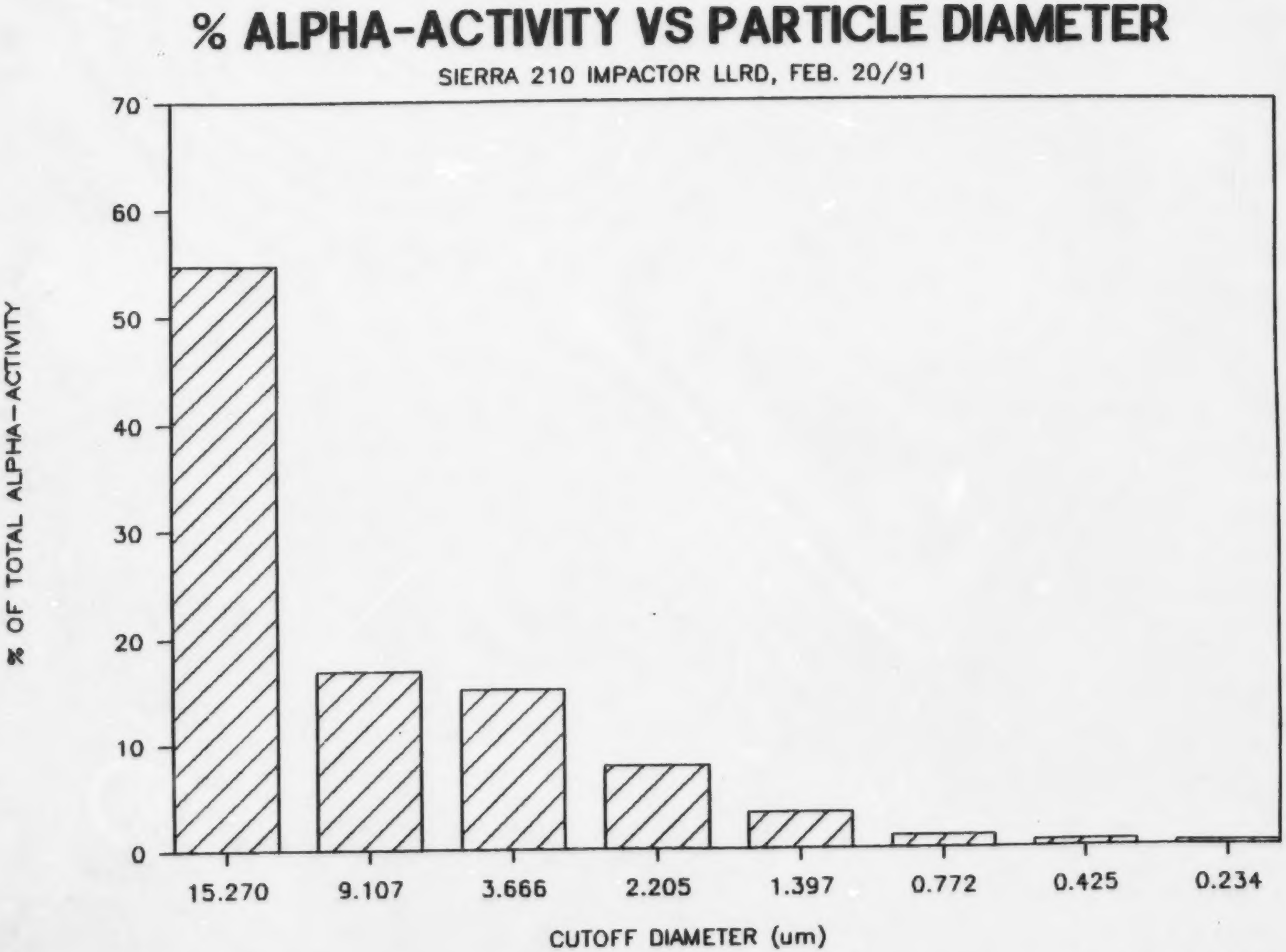


Fig. A30 - Percentage of total α-particle activity versus particle cut-off diameter measured during the yellowcake packaging operation.

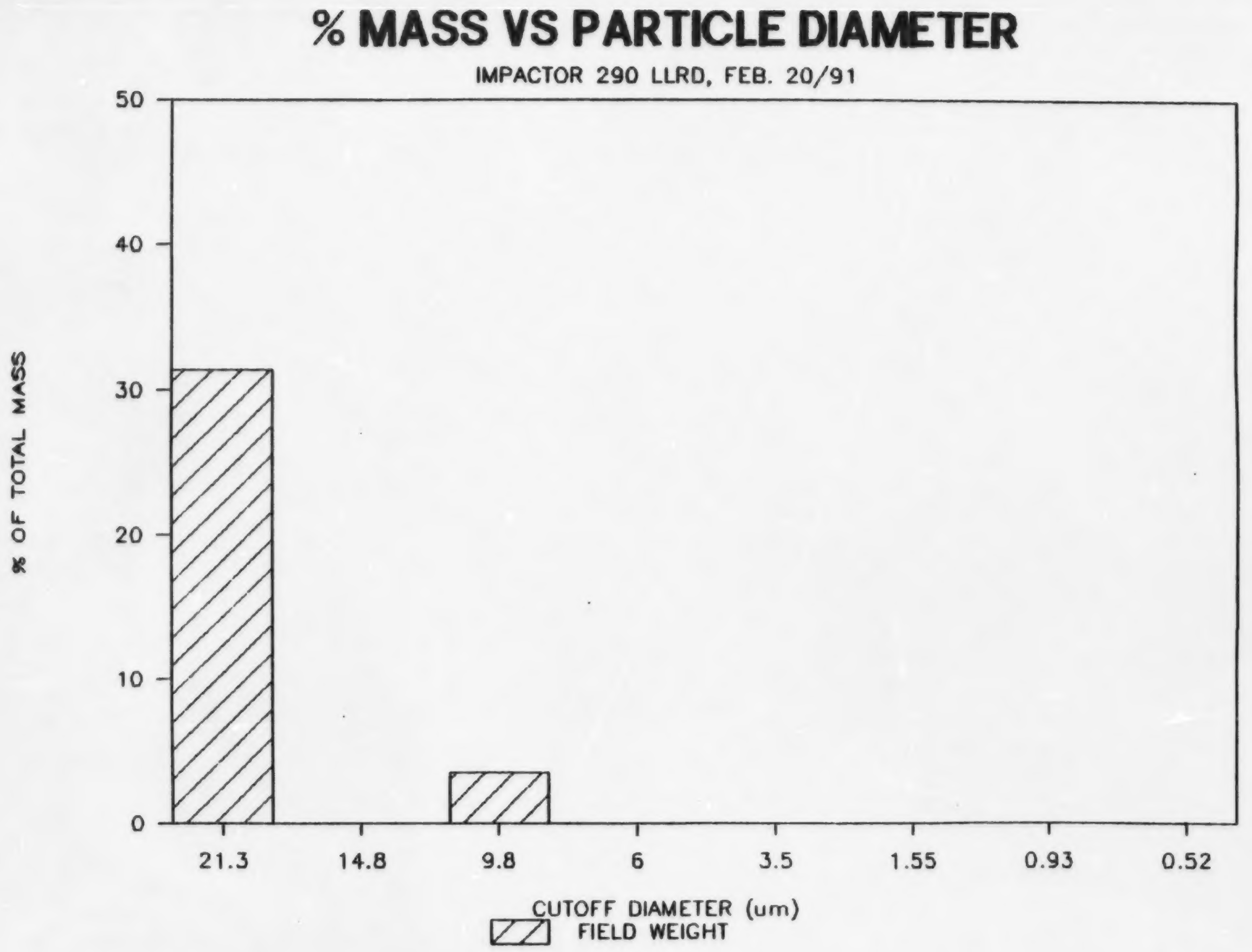


Fig. A31 - Percentage of total mass versus particle cut-off diameter measured during the yellowcake packaging operation.

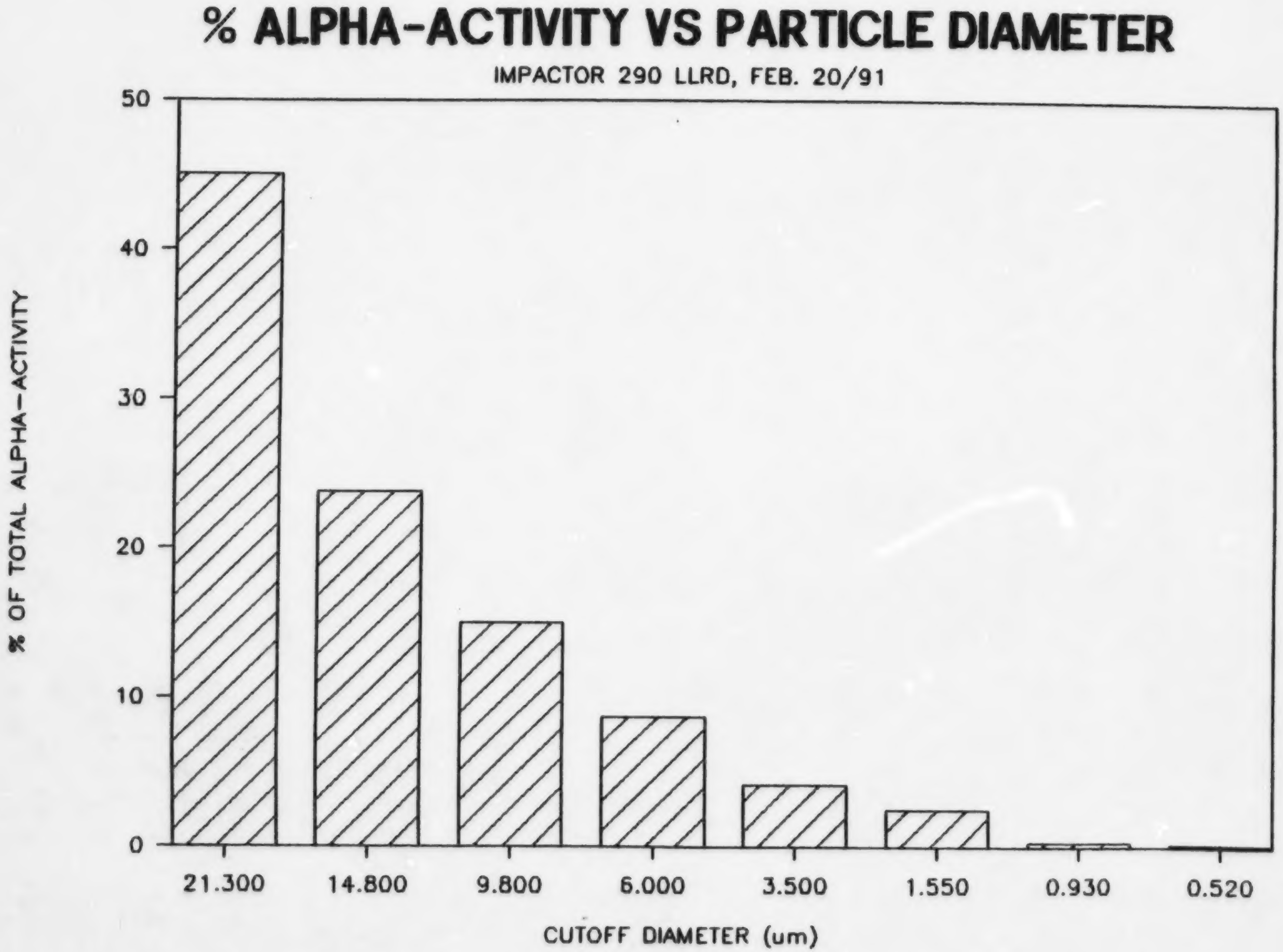


Fig. A32 - Percentage of total α-particle activity versus particle cut-off diameter measured during the yellowcake packaging operation.

APPENDIX B

Because the CLIMET CI-7300 is an optical particle counter, the data obtained with this instrument, i.e., number of particles within a given size range, cannot be compared directly with the data provided by the rest of the instrumentation (dust mass measurements) evaluated and used in the characterization of Long-Lived Radioactive Dust, LLRD, at the two U-mills where this work was conducted (Cluff Lake and Key Lake). For this reason, only some of the data obtained with the above instrument are presented here in a separate Appendix for illustrative purposes only.

Some of the data obtained for several mill operations are shown in Figures B-1 to B-7. Although the graphical representations speak for themselves, a few comments are worth making. The table below gives some data in a summarized form. In this table the symbol ΔD is used to indicate the particle size range(s) within which the maximum number of particles in the distribution is (are) found. The symbol % is used to indicate the percentage of the total number of particles measured of particle size ΔD. Also shown are the dates the data were taken and the milling operations monitored.

Date (1991)	Operation	ΔD (μm)	%	Remarks
Feb. 12th	Conveyor belt	1-5	~70	
Feb. 14th	Milling	0.3-0.7	~70	Bimodal distribution
"	Milling	1-5	~25	
Feb. 15th(1)	Crushing	1-5	55	
Feb. 19th	Lime slaking	0.3-0.7	~80	
Feb. 20th	Yellowcake pack.	0.3-0.7	~80	
Feb. 21st	Yellowcake baghouse filter	0.3-0.7	>80	

The results shown in the above table were to be expected, namely:

a) 'Gross' mechanical operations (such as primary crushing, conveyor belt - primary crushers transfer point, and milling) generated the largest particle size distribution, whereas the final stages of the refining process, or handling of the final product, produced the finest particle size clouds, e.g., lime slaking, yellowcake baghouse filter and yellowcake packaging. (It should be noted that the first three milling operations were monitored at Cluff Lake, whereas the last three operations were monitored at Key Lake.);

b) A large fraction of the dust particles generated in the primary crushing and ore transportation operations were in the range 1 to 5 μm. The milling operation generated a large fraction (~70%) of much smaller particle sizes (0.3 to 0.7 μm), in addition to a substantial fraction of much larger particles, i.e., ~25% in the particle size range 1 to 5 μm. The largest fraction (>80%) of dust particles in the other three milling operations was mainly in the fineparticle size range 0.3 to 0.7 μm;

c) Except for the primary crushing and ore transportation (transfer point between primary crusher and conveyor belt) operations, no significant dust fraction could be measured of particle size greater than 10 μm;

d) The dust concentrations measured at different particle size ranges for any given milling operation were observed to vary relative to one another during the course of the operation. Only one example is given here (see Figures B6 and B7) for illustration purposes. There is a variety of reasons to account for this variability, but the causes are generally related to the particular milling operation under investigation.

The table below shows the total particle concentrations for the same dates and milling operations indicated in the previous table. The data of the table below correspond to the graphs in Figures B-1 to B-7.

Date (1991)	Operation	$[N_T]$ (cm^{-3})	Graph
Feb. 12th	Conveyor belt	133.3	Fig. B-1
Feb. 14th	Milling	34.4	Fig. B-2
Feb. 15th(1)	Crushing	63.2	Fig. B-3
Feb. 19th	Lime slaking	9.9	Fig. B-4
Feb. 20th	Yellowcake pack.	14.5	Fig. B-5
Feb. 21st	Yellowcake baghouse filter	194.5	Fig. B-6
Feb. 21st	"	52.7	Fig. B-7

The number of particles per unit volume (cm^{-3}) within a given particle size range can easily be obtained by multiplying N_T, in the above table, by the percentage of the total number of particles within this size range, which can be read directly from Figures B-1 to B-7.

It should be noted that because of the relatively large size, and hence mass, of the particles to which the CI-7300 is sensitive, the particulate concentrations measured by this instrument do not seem excessive. However, the particle concentration increases markedly for smaller particle sizes.

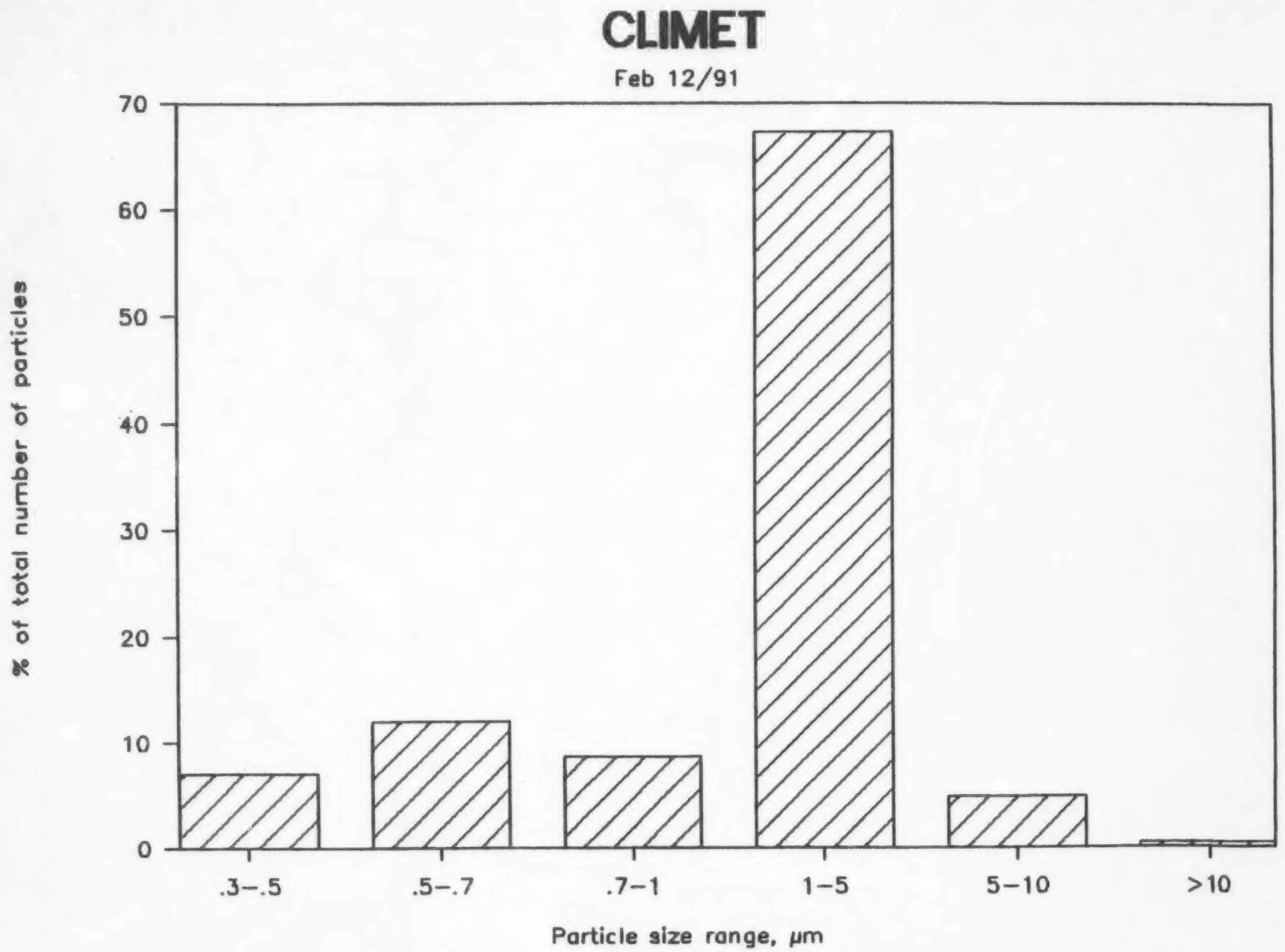


Fig. B1 - Percentage of total number of particles versus particle size range measured at the crusher/conveyor belt transfer point.

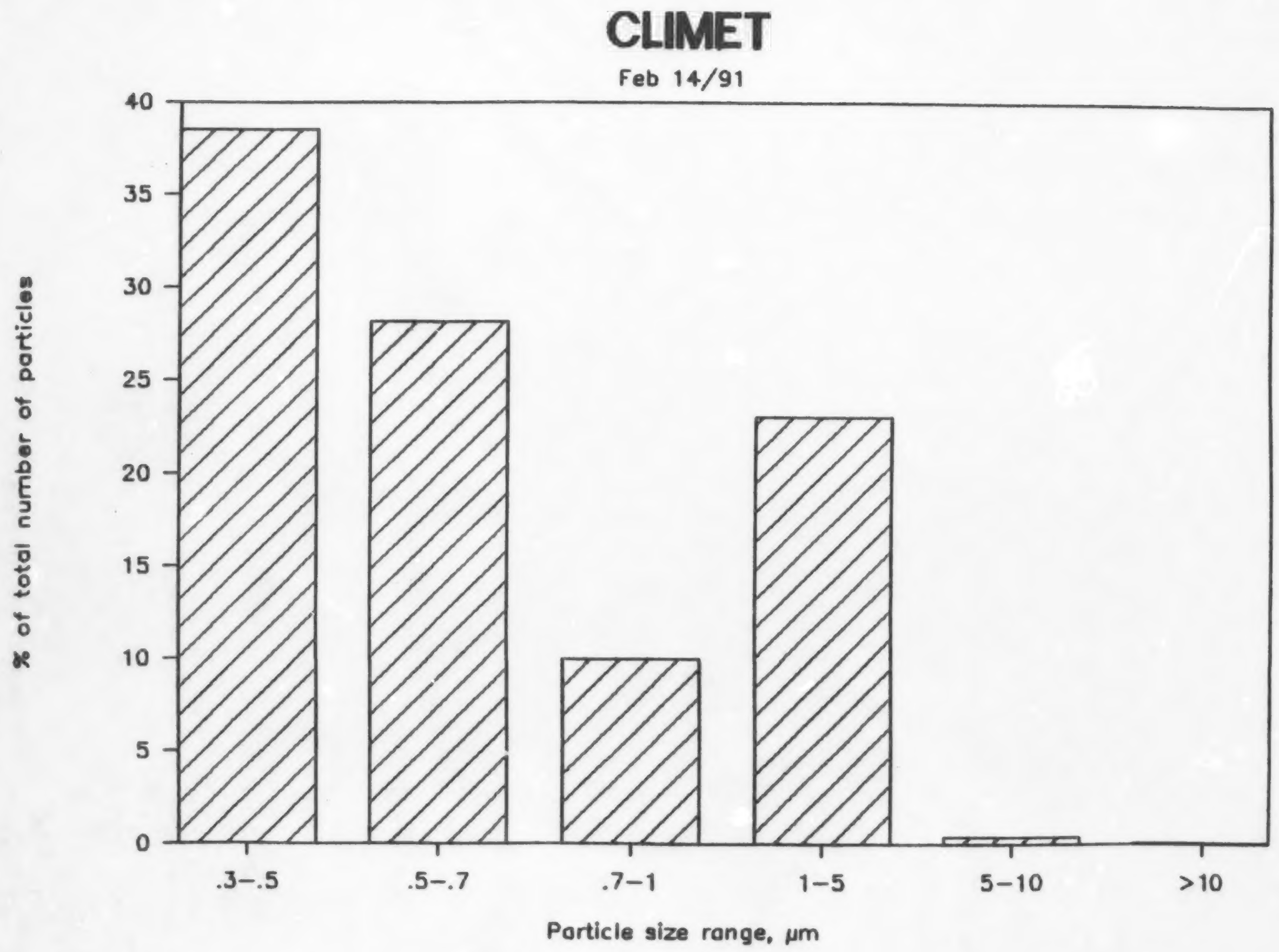


Fig. B2 - Percentage of total number of particles versus particle size range measured during the ball milling operation.

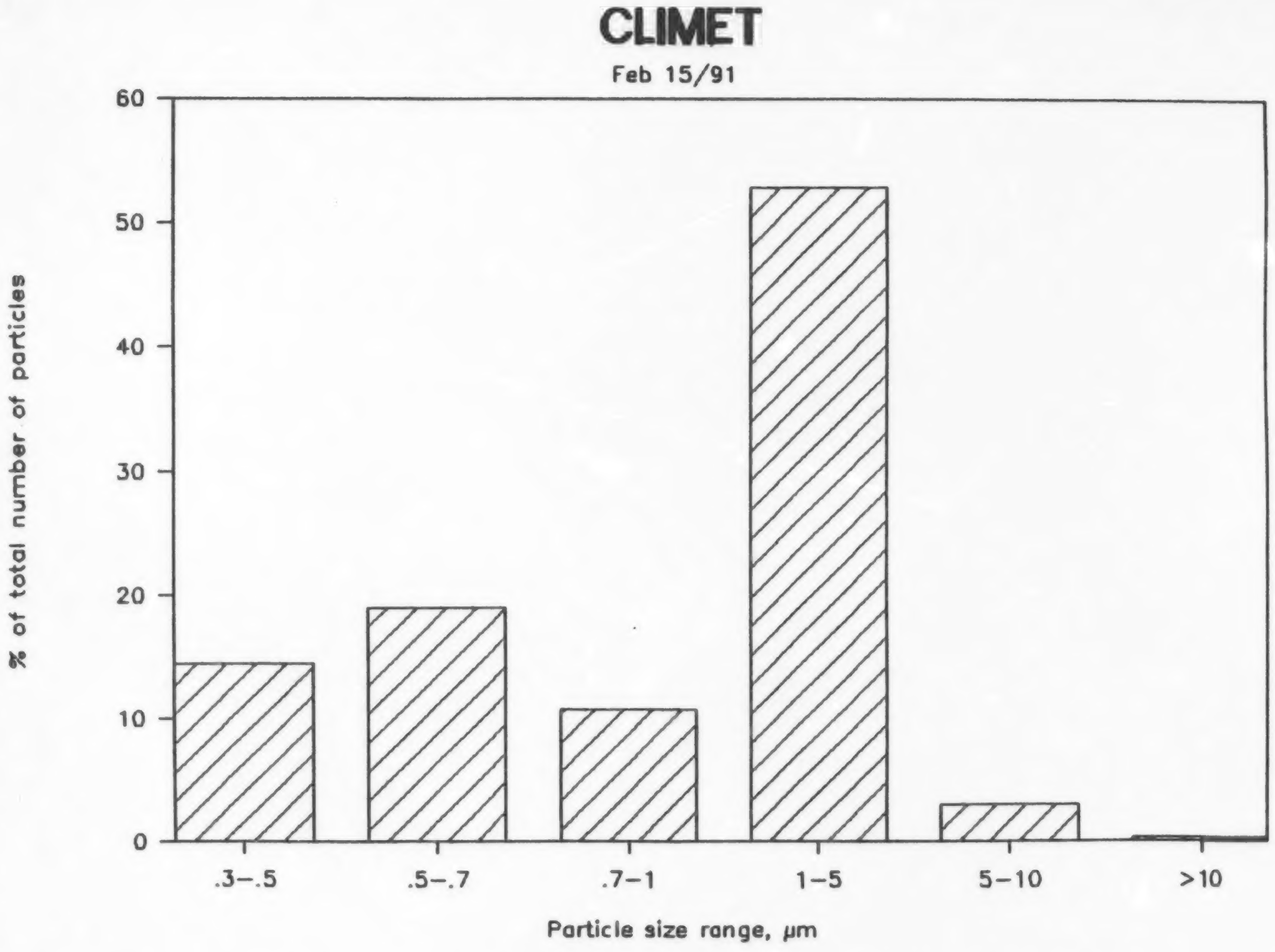


Fig. B3 - Percentage of total number of particles versus particle size range measured during the cone crushing operation.

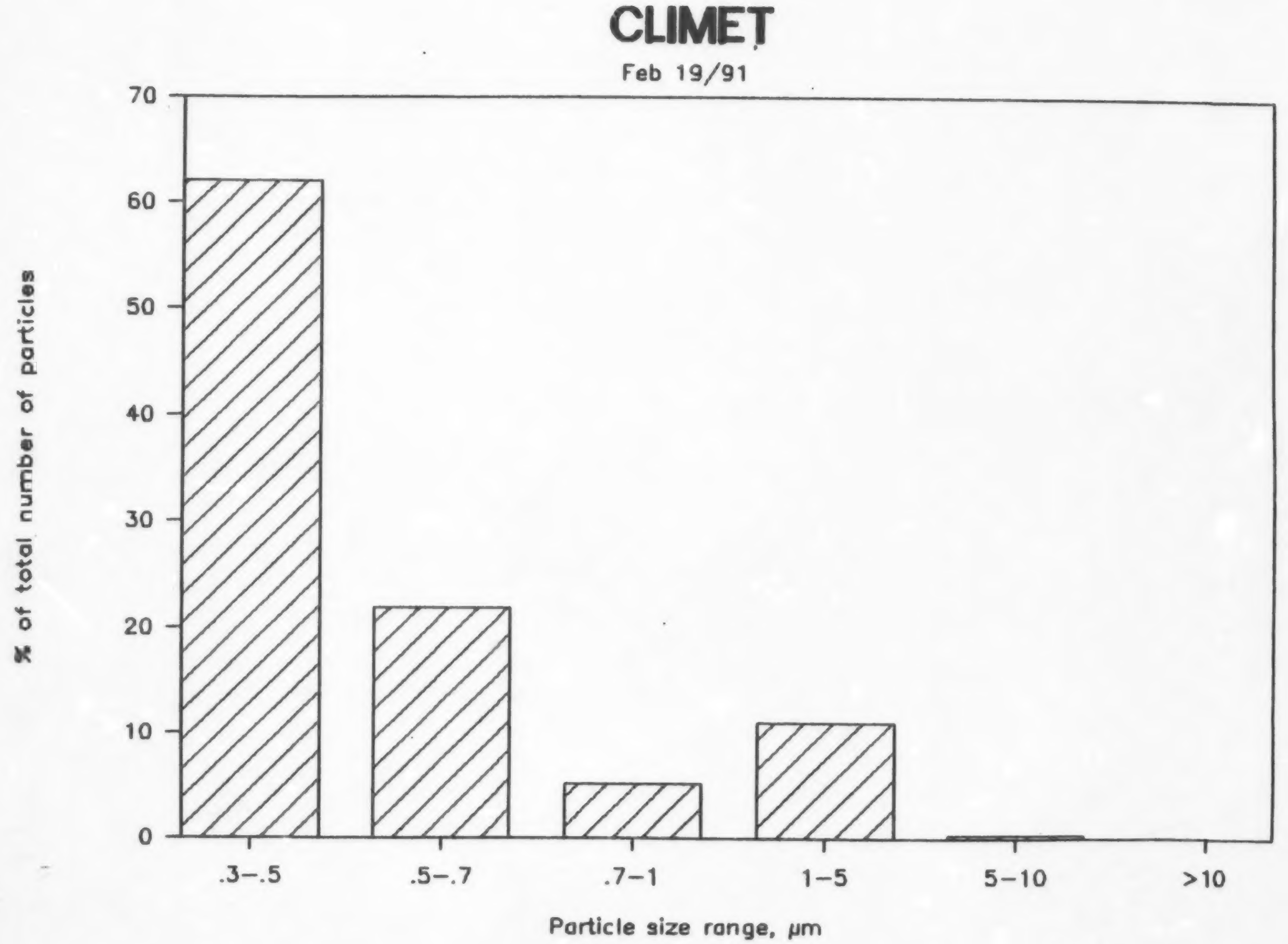


Fig. B4 - Percentage of total number of particles versus particle size range measured during the lime slaking operation.

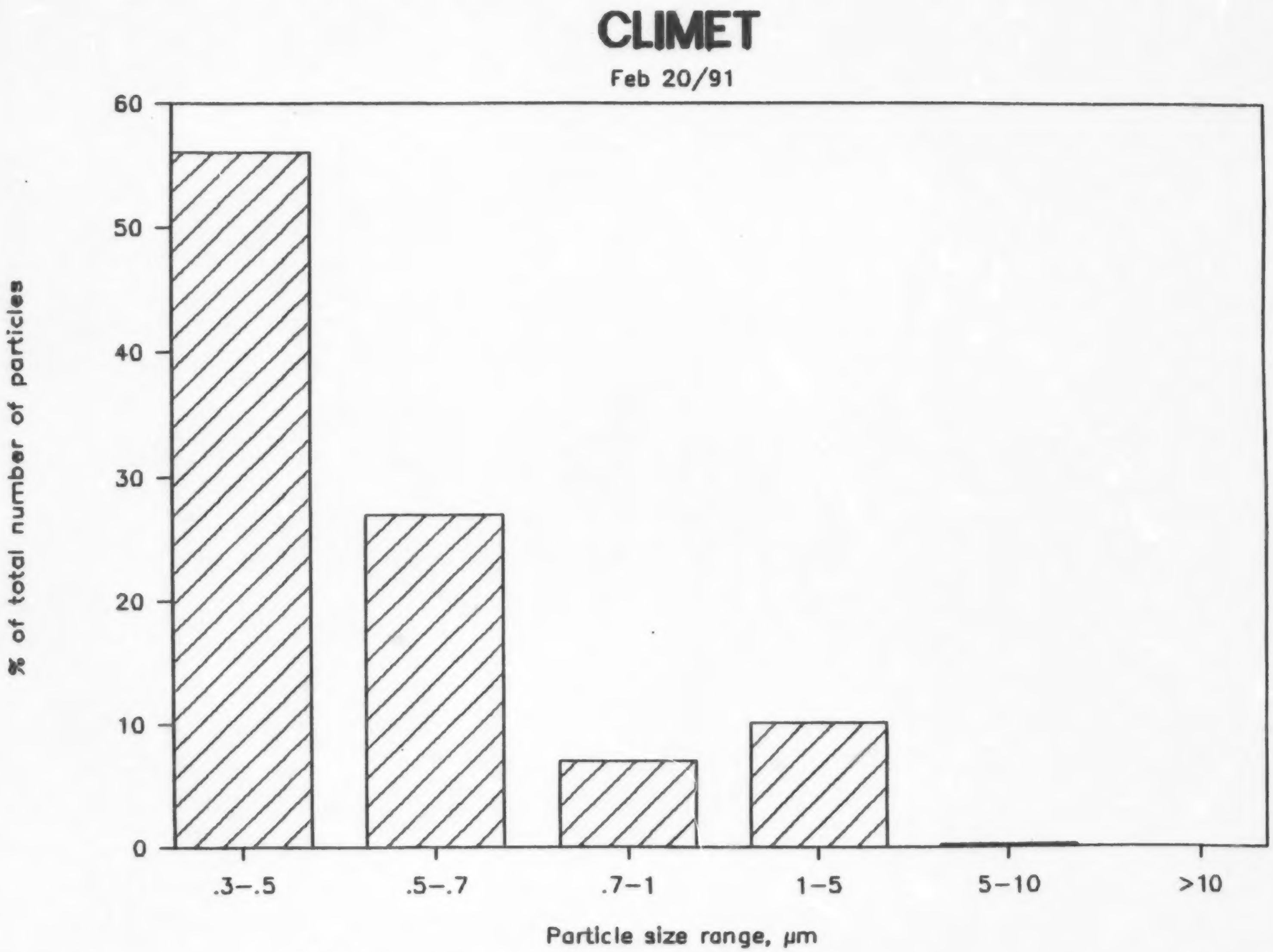


Fig. B5 - Percentage of total number of particles versus particle size range measured during the yellowcake packaging operation.

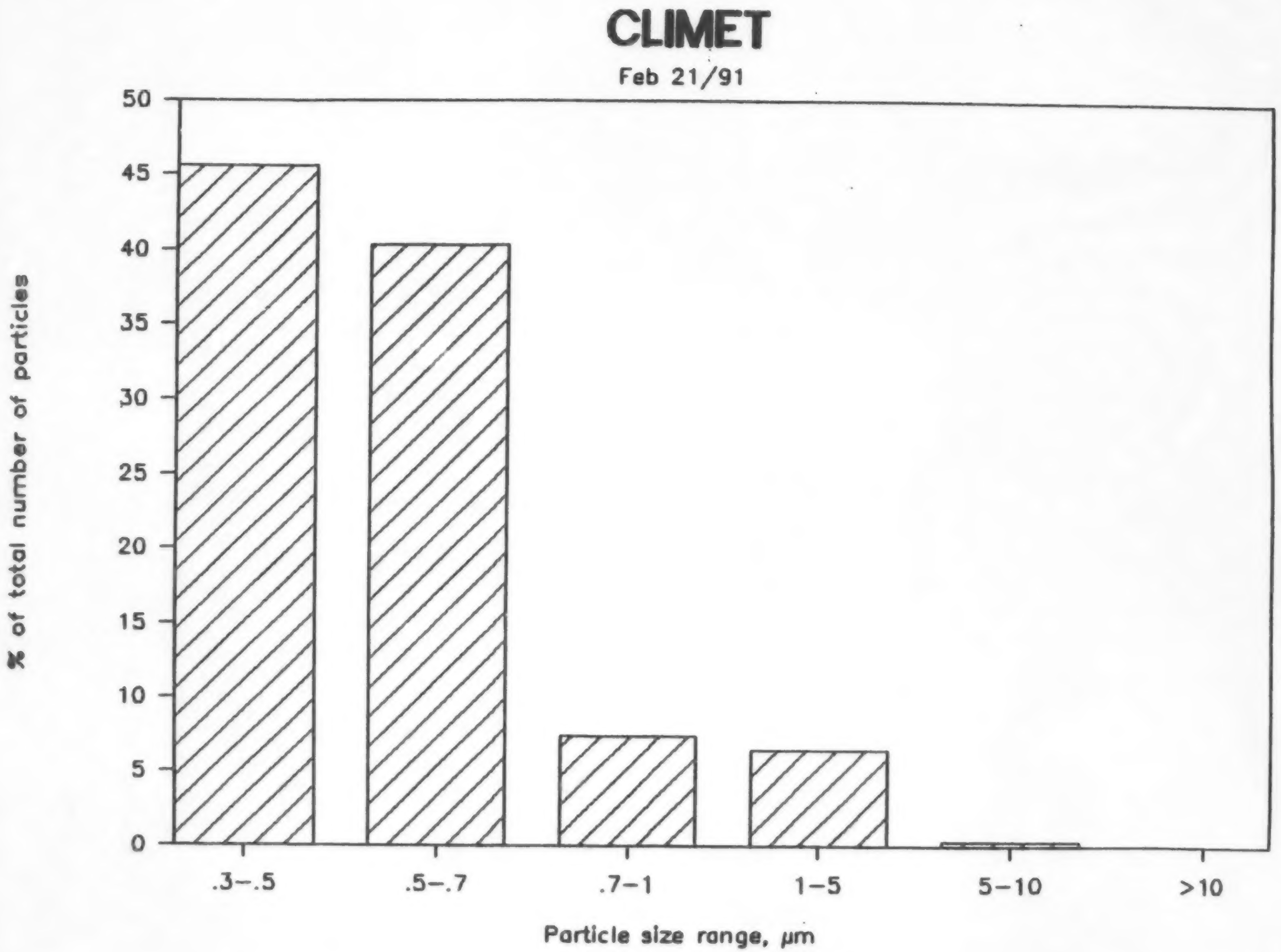


Fig. B6 - Percentage of total number of particles versus particle size range measured at the yellowcake baghouse filter site.

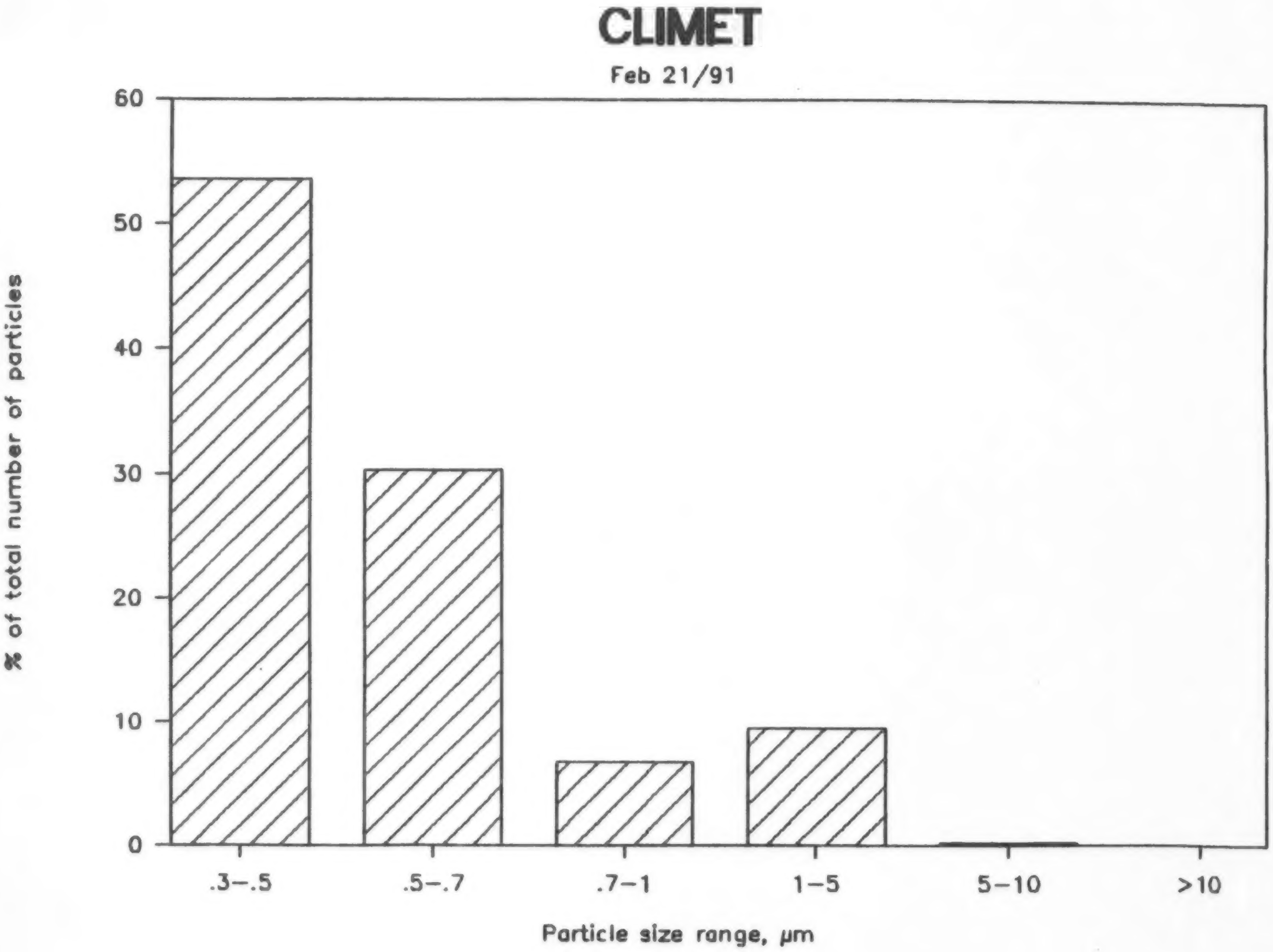


Fig. B7 - Percentage of total number of particles versus particle size range measured at the yellowcake baghouse filter site.